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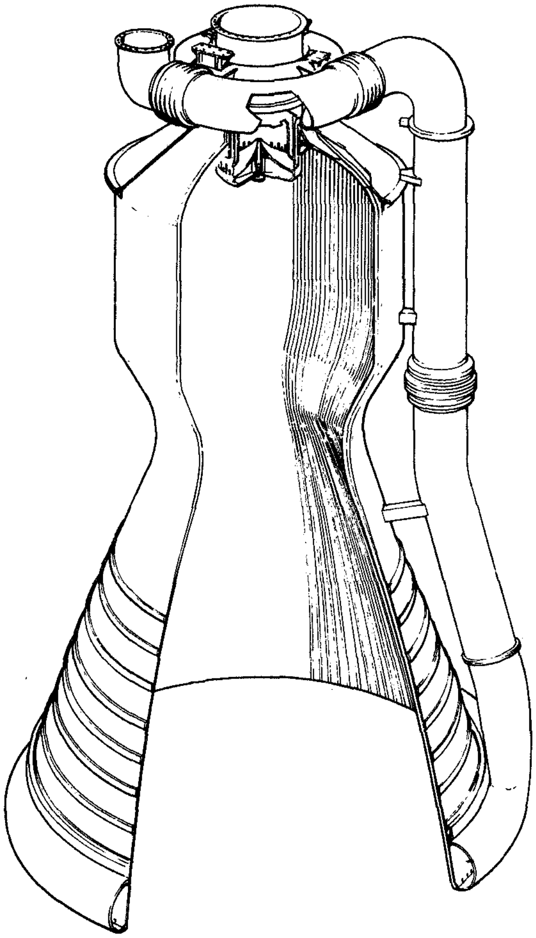

FEASIBILITY STUDY OF A PRESSURE-FED ENGINE FOR A WATER RECOVERABLE SPACE SHUTTLE BOOSTER

DESIGN DATA BOOK

15 MARCH 1972

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

TRW SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH • CALIFORNIA

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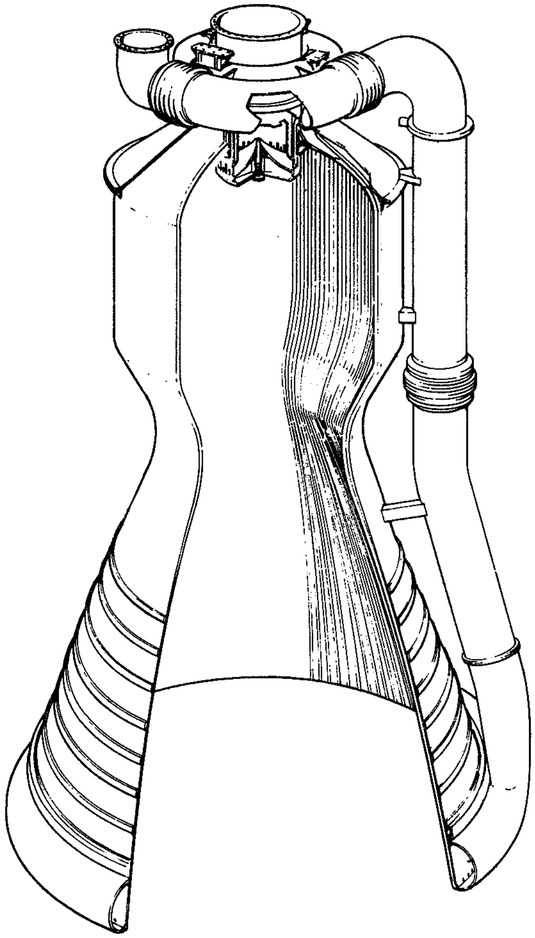

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TRW SYSTEMS
DESIGN DATA HANDBOOK
FOR THE PRESSURE FED ENGINE STUDY

Prepared For
National Aeronautics & Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Under Contract
NAS8-28218

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Approved By: H Burge
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Program Manager
Pressure Fed Engine Study

CONTENTS

INTRODUCTION

This report has been prepared in partial fulfillment of Contract NAS 8-28218 "Feasibility Study of a Pressure-Fed Engine for a Water Recoverable Space Shuttle Booster." During the initial portion of this contract a gimbaled, regeneratively cooled, fixed thrust engine having a coaxial pintle injector was selected as optimum for this configuration. This report presents the preliminary operating specification, envelopes and weight for the selected engine system, subsystems and other CEI's.

Since the initial trade studies documented the attractiveness of two other engine configurations, i.e., a hinge nozzle using a Techroll® seal, and a regeneratively cooled engine using liquid injection thrust vector control (LITVC), details are also presented for these configurations. Detailed engine analysis and design trade studies leading to the selection of a regeneratively cooled gimballed engine and pertaining to the selection of the baseline design configuration may be found in the Final Report. (NASA-MSFC Control Number SE-019-011-2H-B).

1.0 TRW PRESSURE FED ENGINE

1.1 Engine Configuration

The design approach to the TRW PFE has been one of simplifying the engine to its most rudimentary functions. The engine features a 24" diameter centrally located injector with oxidizer entering the engine axially as shown in Figure 1.1-1. The diameter of the oxidizer feeder is set identical to the vehicle feed ducting and flow velocities are on the order of 20 fps. The oxidizer is turned at the injector tip and enters the chamber radially through 36 primary and 36 secondary slots. These slots are on the order of 3" x 0.7" and as such do not possess any critical tolerance dimensions. The fuel flows through ~0.7" annulus in an axial direction where it intercepts the radially flowing oxidizer. The effect of dimensional differences on these metering orifices is not critical. They are easily cut by standard manufacturing practices and readily inspected. The cryogenic oxidizer temperatures are separated from the ambient temperature fuel by a void to prevent undesireable temperature interactions. Ignition is achieved with standard TEA/TEB, similar to the F-1 system.

The fuel enters the engine through an external feeder duct of nominal 14" diameter. A single counter pass regenerative cooling circuit is utilized. The fuel enters the injector at an estimated 200°F temperature higher than the supply temperature.

The propellant shutoff valves are of the wafer type and serve only as on-off valves. The actuators would be driven by: (1) APU hydraulic power, or (2) the pressurized RP-1, or (3) the pressurization system gases. These valves are ~14" for the fuel and ~16" for the oxidizer.

The tube bundle consists of 940 tubes. The approach taken is to select a tubing sizing which is of standard mill run. The tubes are then shaped only with respect to width in the chamber with no tube wall drawing required. This means a constant wall thickness, constant perimeter tube is possible, resulting in minimum tube costs. There are no critical dimensions for the tube bundle for the low heat flux PFE.

The chamber shell extends to an area ratio of ~1.4:1. The remainder of the nozzle is banded. The entire shell, tube, and banding is integrally brazed as a unit.

The gimbal mount is a 4 bearing mount, placed around the oxidizer inlet in a symetrical gimbal ring.

The life of the engine is predicted to easily meet a mission requirement of 50 missions from a pressure and thermal fatigue standpoint. This life is particularly enhanced by using all the fuel for cooling to minimize the tube wall temperatures.

The engine is fabricated from INCO 718 for high corrosion resistance. The weight of the engine is 11,467 lbs dry and 14,956 lbs wet; these weights result in higher thrust/weight ratios than conventional engines can give, primarily because of the 660 lb injector element.

The overall envelope of the engine is ~172.8" O.D. by 261.5" to the plane of the gimbal ring as shown in Figures 1.1-3 and 1.1-4.

1.1.2 Engine Characteristics

PARAMETER	REQUIREMENT
Sea Level Thrust *	1.2×10^6 lbf
Sea Level Steady State Thrust Repeatability *	+ 36,000 lbf - 36,000 lbf
Vacuum Thrust Level *	1.47×10^6 lbf
Vacuum Thrust Level Repeatability *	+ 45,000 lbf - 45,000 lbf
Propellants	
. Oxidizer	LOX
. Fuel	RP-1
Mixture Ratio	2.4
Mixture Ratio Tolerance *	± 0.048
Propellant Utilization Mixture Ratio Variation (Allowable Maximum)	± 0.24
Chamber Pressure (Nominal)	250 psia
Nozzle Expansion Ratio	5:1
Interface Pressures (Minimum Required)	
. Oxidizer	360 psia
. Fuel	380 psia
Propellant Supply Temperatures	
. Oxidizer	-280°F
. Fuel	+65°F
Sea Level Specific Impulse (Nominal)	227.3 lbf sec/lbm

Sea Level Specific Impulse (3σ minimum)	225.0 lbf sec/lbm
Vacuum Specific Impulse (Nominal)	276.0 lbf - lbf sec/lbm
Vacuum Specific Impulse (3σ minimum)	273.3 lbf - lbf sec/lbm
Throttle Range	
. Pressure	To 70% of Engine Thrust
. Engine	<60% of Engine Thrust
Throttle Response	1 second (90% of Commanded Change)
Static Envelope	
. Length (overall)	275 inches
. Length (from Gimbal center line)	262 inches
. Exit Diameter	173 inches
. Head End Radius	69 inches
Thrust Vector Control (TVC) System	Gimbal (baseline)
TVC Angle	$\pm$ 6°
TVC Slewrate	10 deg/sec
TVC Acceleration	3 rad/sec^2
TVC Bandwidth	8 CPS
Mission Burn Time	150 seconds
Life (MBO)	50
Startup Time (to 90% Pc)	3 $\pm$ 0.050 seconds
Startup Overshoot (Pc)	25 psi
Startup Overshoot (Pc settling time)	200 ms
Startup Rate (maximum)	700,000 lbs/sec maximum
Shutdown Rate	TBD
Minimum Shutdown Time (to 10% Pc)(Engine Capability)	1.0 seconds
Shutdown Impulse Repeatability (Engine Capability)	$\pm$ 40,000 lbf/seconds
Side Load Moment	Equivalent 20g lateral Acceleration
Slap Down Loads	20g, TBD Impact Velocity
Thrust Vector Alignment	$\pm$ .25°
Maximum Outside Surface Temperature	300°F
Electrical Power	300 Watts maximum
. Startup	200 watts maximum
. Steady State	200 watts maximum
. Shutdown	200 watts maximum

PARAMETER	REQUIREMENT
Number of Starts (MBO)	100
Propellant Filtration	2500μ
Shutdown Mode	Injector Face Shutoff
Command Voltage Range (Inclusive all operations)	0-10 V
Combustion Stability (100% Overpressure Bomb Recovery - measured to ± 10% nominal Pc)	50 M.S.
Weight	
. Dry	12,000 lbs
. Wet	15,500 lbs
Moment of Inertia (Wet) (measured about engine gim al)	
. Ixx	5056 SL FT^2
. Iyy	28895 SL FT^2
Actuation Mechanisms	
. SOV	Pneumatic - 380 psia
. Throttle Actuator	Hydraulic (Fuel) - 380 psia
. Gimbal Actuator	Hydraulic (Fuel) - 3000 psia
SOV Leakage	10 SCIM GN_2 @380 psia
Structural C teria	MSFC Handbook - 505
. Min. Yield F.S.	
. Min. Ult. F.S.	
. Proof Pressure Factor	
. Burst Pressure	
Material Prop. & Design Allow.	MIL-HDBK-5
Fracture Mechanics Criteria	Yes
Dynamic Stability Requirement	Yes
Failure Criteria	
. Electrical	FO/FS
. Mechanical	F/S

* DEFINED AT NOMINAL CONDITIONS

1.2 Injectior

1.2.1 The TRW approach to the injector for the Pressure Fed Engine is the coaxial pintle element centrally located in the head end of the engine.

This approach incorporates all the advantages inherent in the coaxial

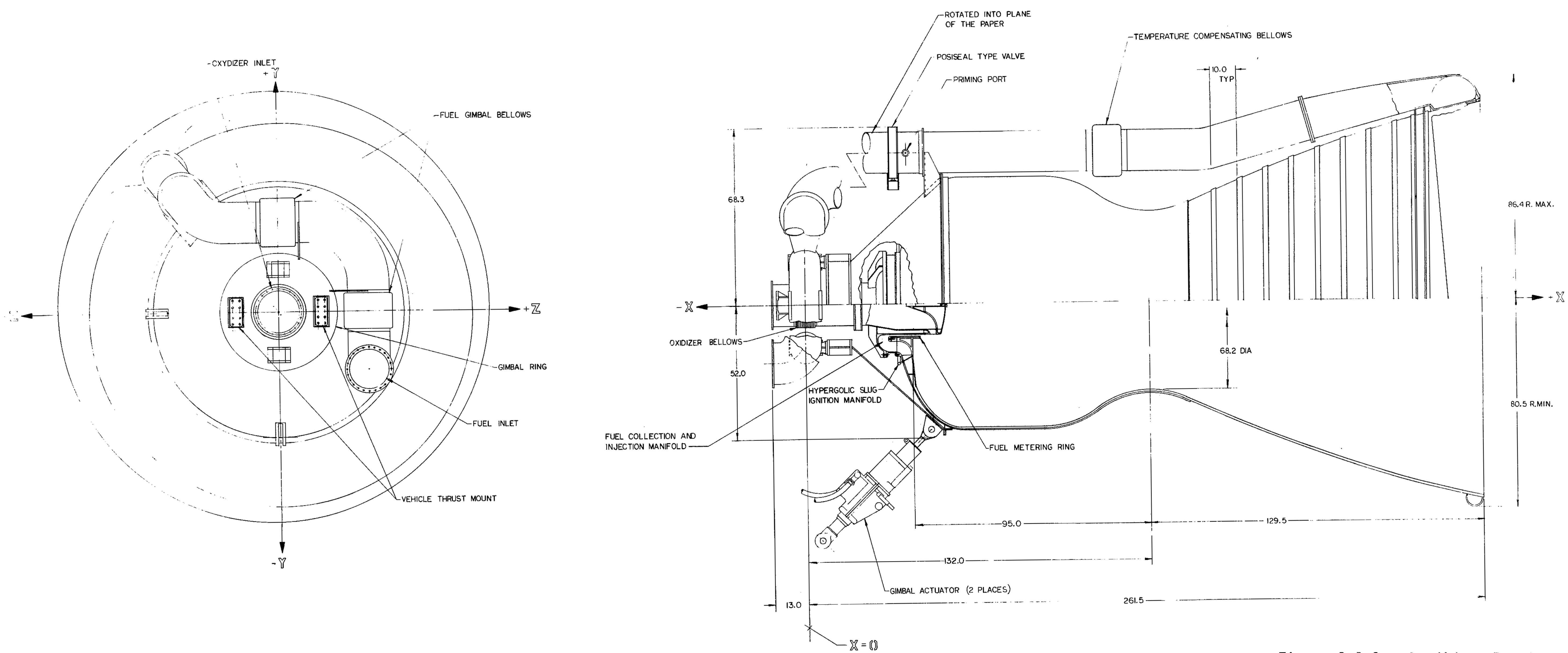


Figure 1.1-1. Candidate Pressure Fed Engine

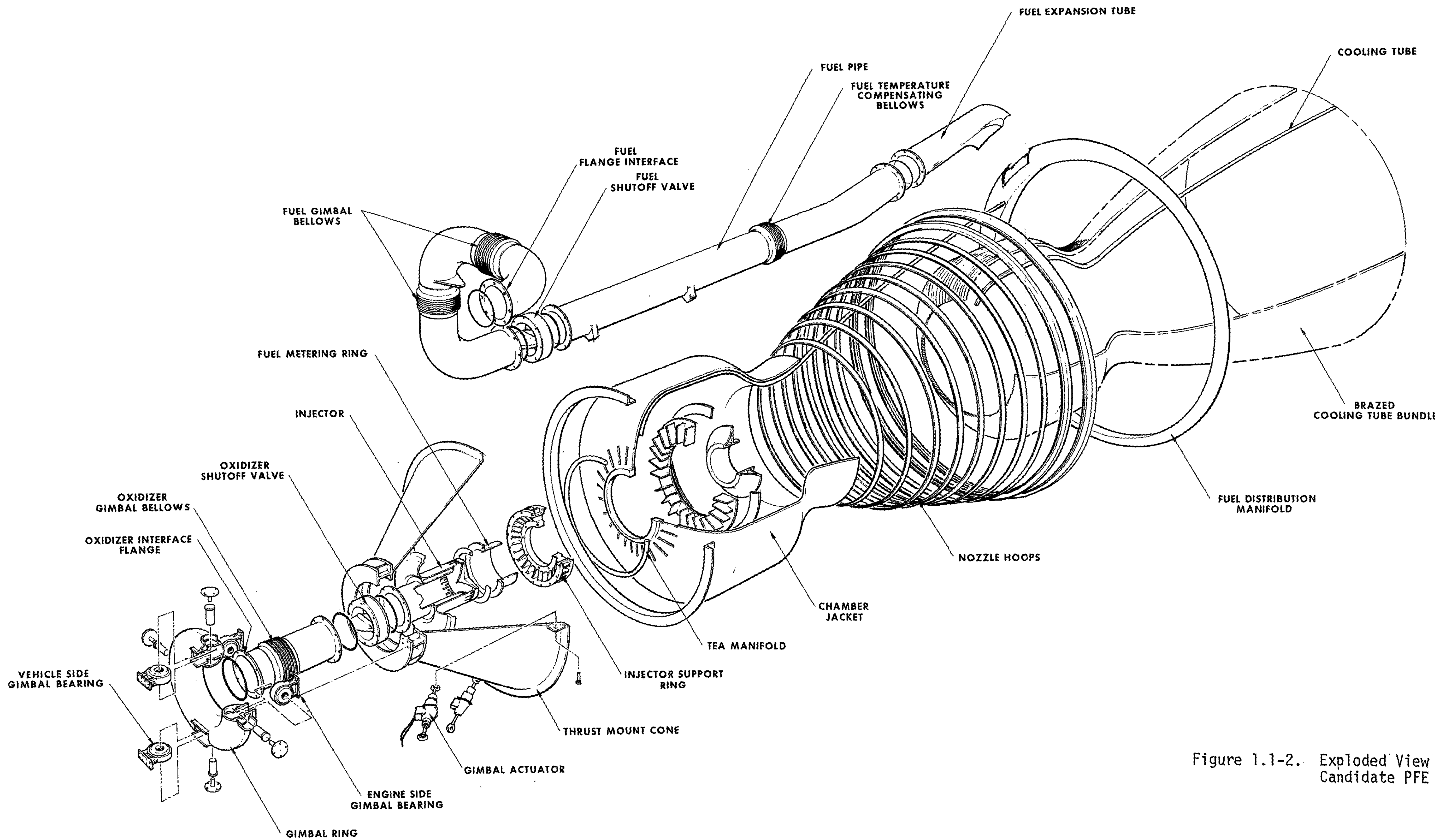


Figure 1.1-2. Exploded View Candidate PFE

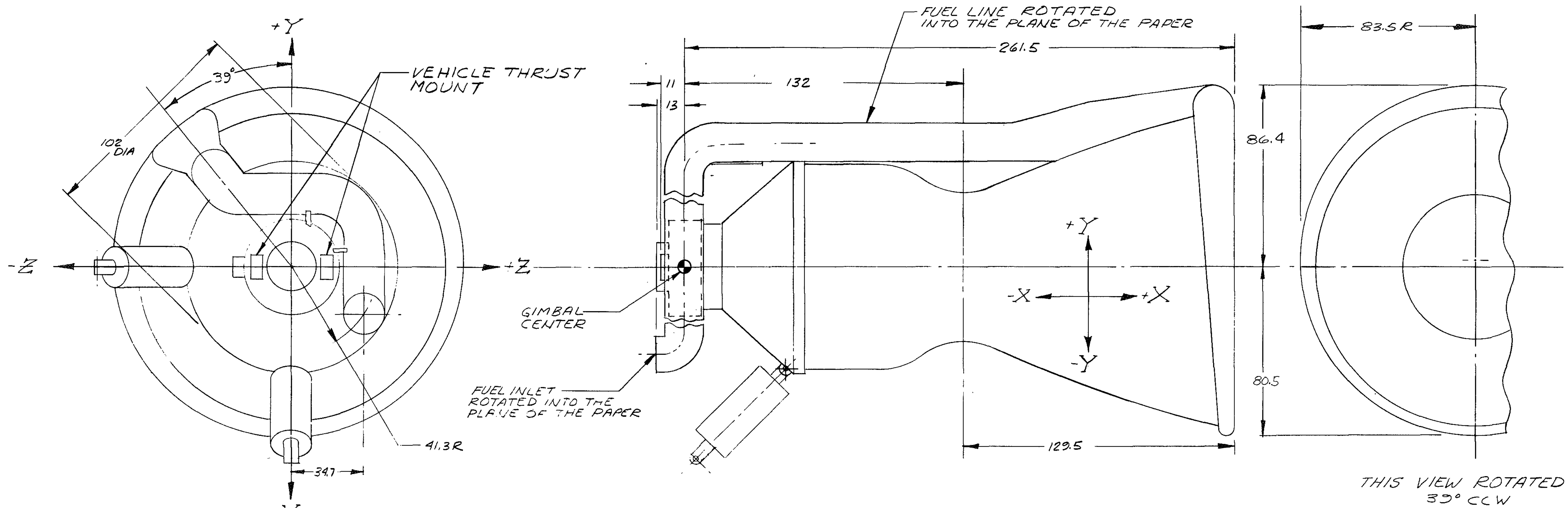


Figure 1.1-3. Static Envelope — Candidate PFE

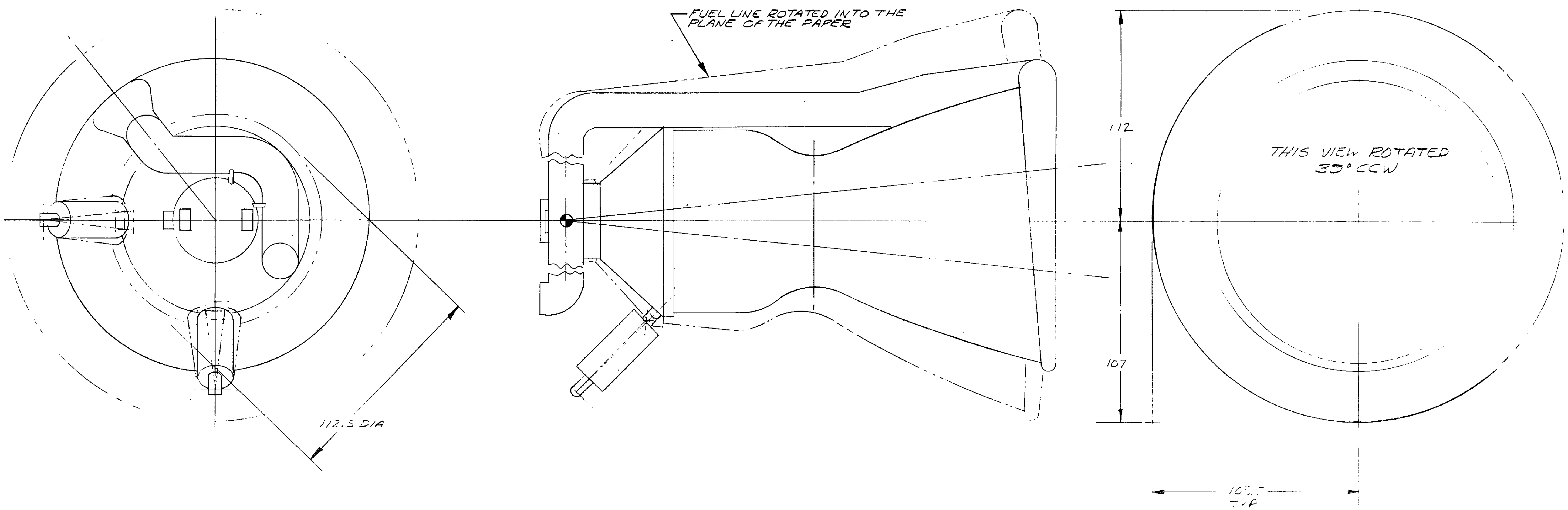


Figure 1.1-4. Dynamic Envelope — Candidate PFE

pintle injector. The injection slots are uncomplicated and do not require close manufacturing tolerances. They are relatively large and virtually impossible to plug. The pintle tip is cooled by a film of oxidizer injected at the center and flowing radially outward over the surface. Only 20 lbs/sec of oxidizer (a very small percentage of total flow) is required to keep the surface to 500°F maximum.

Figure 1.2-1 shows the injector details, geometry and sizes. It is drawn to reflect the simple application of this approach to both the duct cooled and regeneratively cooled chamber configurations.

The left half of the figure shows the fuel distribution manifold and internal porting for fuel to the primary injection sheets and to the duct tube bundle. The right half shows how fuel, already circumferentially distributed in the regen inlet manifold, is collected from the regen tube bundle and ported directly to the primary fuel injection sheet. In both cases, the injector element is readily removeable and replaceable.

The fuel flow over a distribution weir and then axially into the chamber in a 0.7" continuous annular sheet approximately 24 in. diameter.

The oxidizer enters the central element axially from the head end. It is turned and injected into the chamber radially through 36 primary and 36 secondary injection slots to impinge on the annular fuel sheet.

Also shown is the ease of injecting a hypergol start slug directly on the initial oxidizer flow with this approach.

	OXIDIZER	FUEL
Flow Rate #/sec	3730	1550
Pressure in PSIA	352	303.4
Pressure drop PSID	90	41.4
Weight lbs	660	

1.3 Combustion Chamber

1.3.1 The combustion chamber/nozzle design chosen during the Pressure Fed Engine Study is a regeneratively cooled, single pass counter flow configuration shown in Figure 1.3-1. It consists of a brazed cooling tube bundle retained by a pressure shell in the combustion chamber portion and bands in the nozzle. The pressure shell extends past the throat to an expansion area ratio of 1.4:1 on the nozzle. The tube bundle is brazed integrally with the pressure shell and bands. A full inlet manifold at the exit plane circumfrencially distributes the fuel which then flows

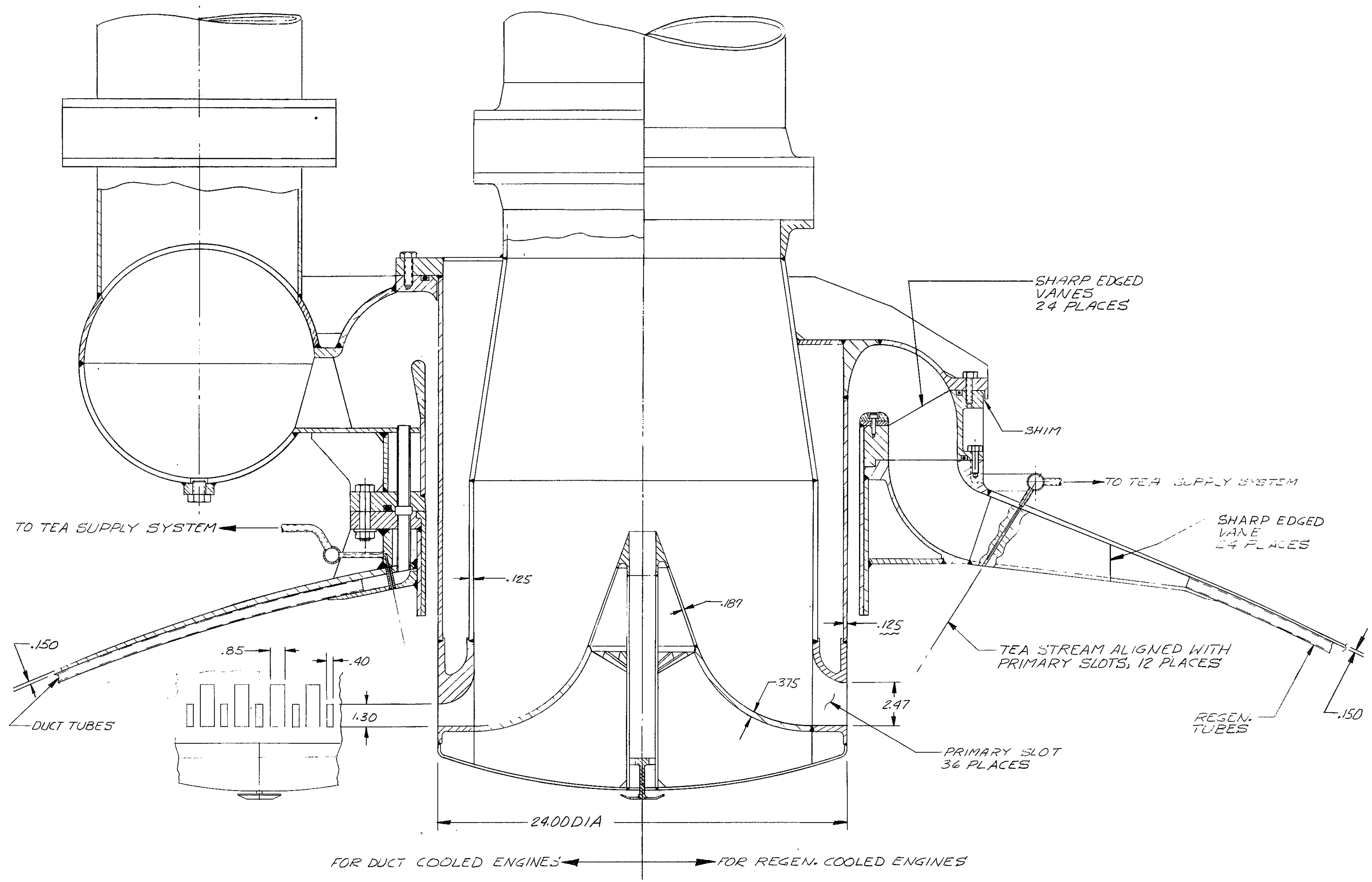


Figure 1.2-1. Injector Detail

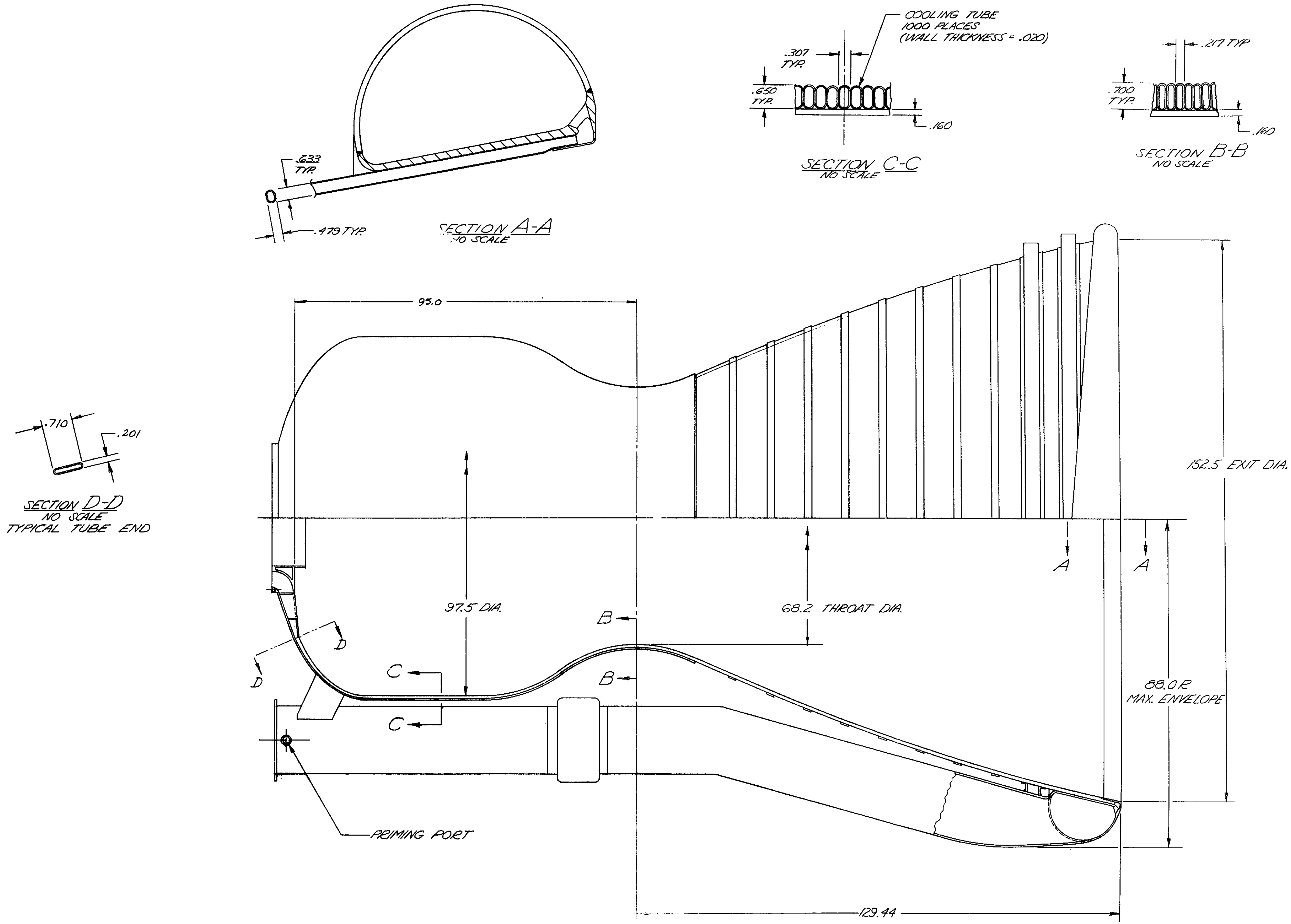


Figure 1.3-1. Candidate Regeneratively Cooled PFE Chamber 1200K ($\epsilon = 5$)

through the tubes to the injector. The fuel temperature rise is approximately 200°F.

The material used is Inconel 718 for corrosion resistance and thermal cycle life considerations. The thermal stress design of the tubes does not establish severe wall thickness requirements, thereby allowing the use of constant wall thickness and constant perimeter tubes. Slight changes in wall thickness due to tube forming are easily accomodated. This feature allows the use of one size tubing throughout the engine. The resulting final cross section of the tubing is shown in the details.

The propellant duct which feeds the inlet manifold is a 14 inch diameter, Inconel 718 line with .100 wall thickness and incorporates a thermal expansion compensating bellows.

1.3.2 Characteristics

Chamber Diameter (inches)	97.5
Throat Diameter (inches)	68.2
Length inches	224.4
Exit Diameter (inches)	152.5
Contraction Ratio	2
Expansion Ratio	5
Chamber Pressure (PSIA)	250
Tube Bundle Pressure Drop (PSID)	68
Weight (LBS)	6351

1.4 Shutoff Valves

1.4.1 The shutoff valves, Figure 1.4-1, are externally actuated butterfly valves. The valves are operated 1 full cycle each mission. They are opened at the ignition signal and closed to cause engine cut-off. The external actuation can be hydraulic power from an APU, fuel from tank pressure, or it can be pneumatic pressure from fuel tank pressurant gas. Hydraulic power is preferred for more accurate control, however, response time can be met with any of the above methods.

The butterfly valve manufactured by Posiseal Inetrnational Inc. has been selected for detailed design evaluation. Valve proportions have been predicated on a trimmed down version of the industrial design and the actuators have been sized based on torque data supplied by the vendor.

Valve port sizes of 16" (LOX) and 14" (RP-1) have been selected based on engine design and system weight trade-off studies. A flight scaled

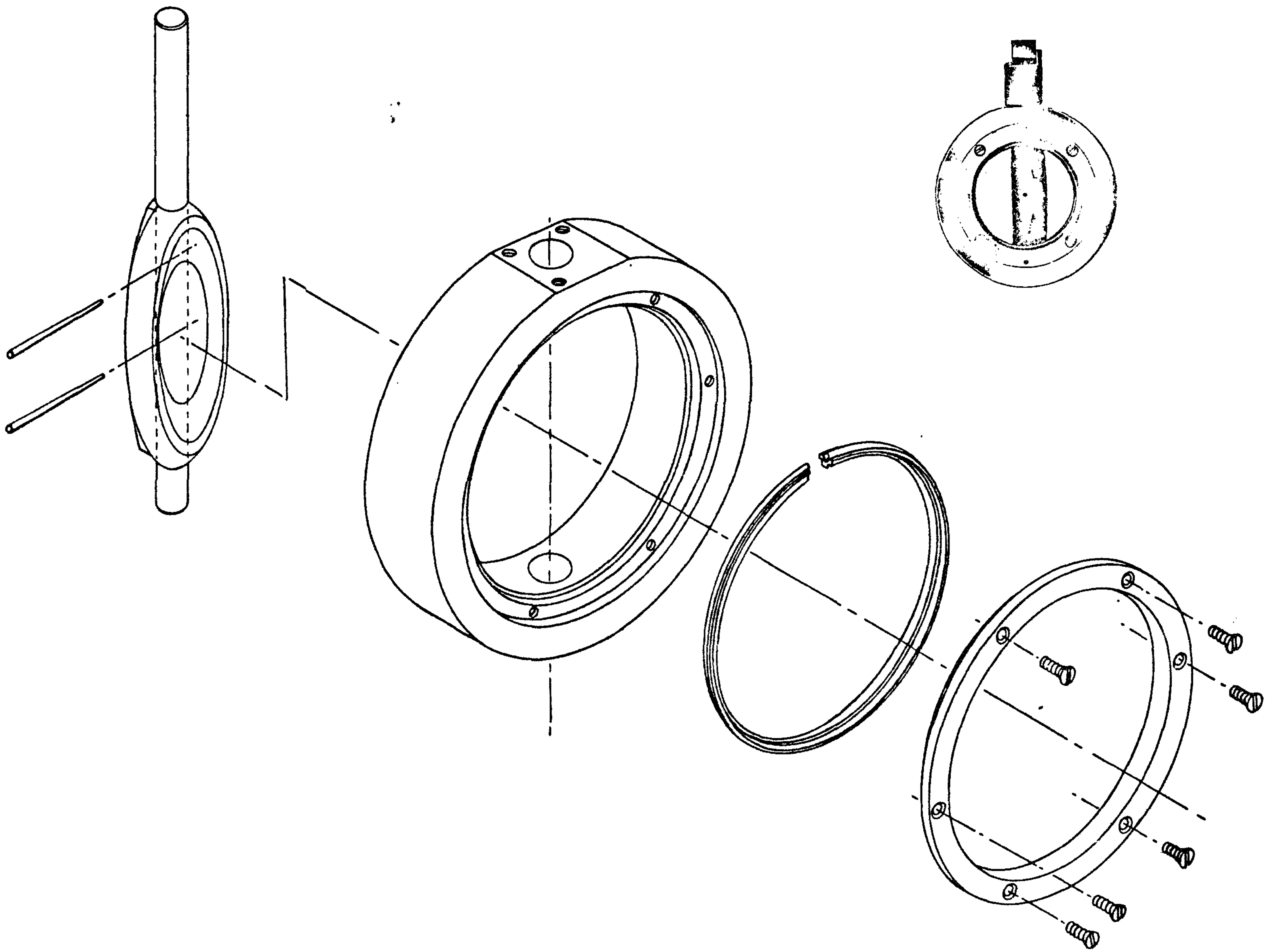
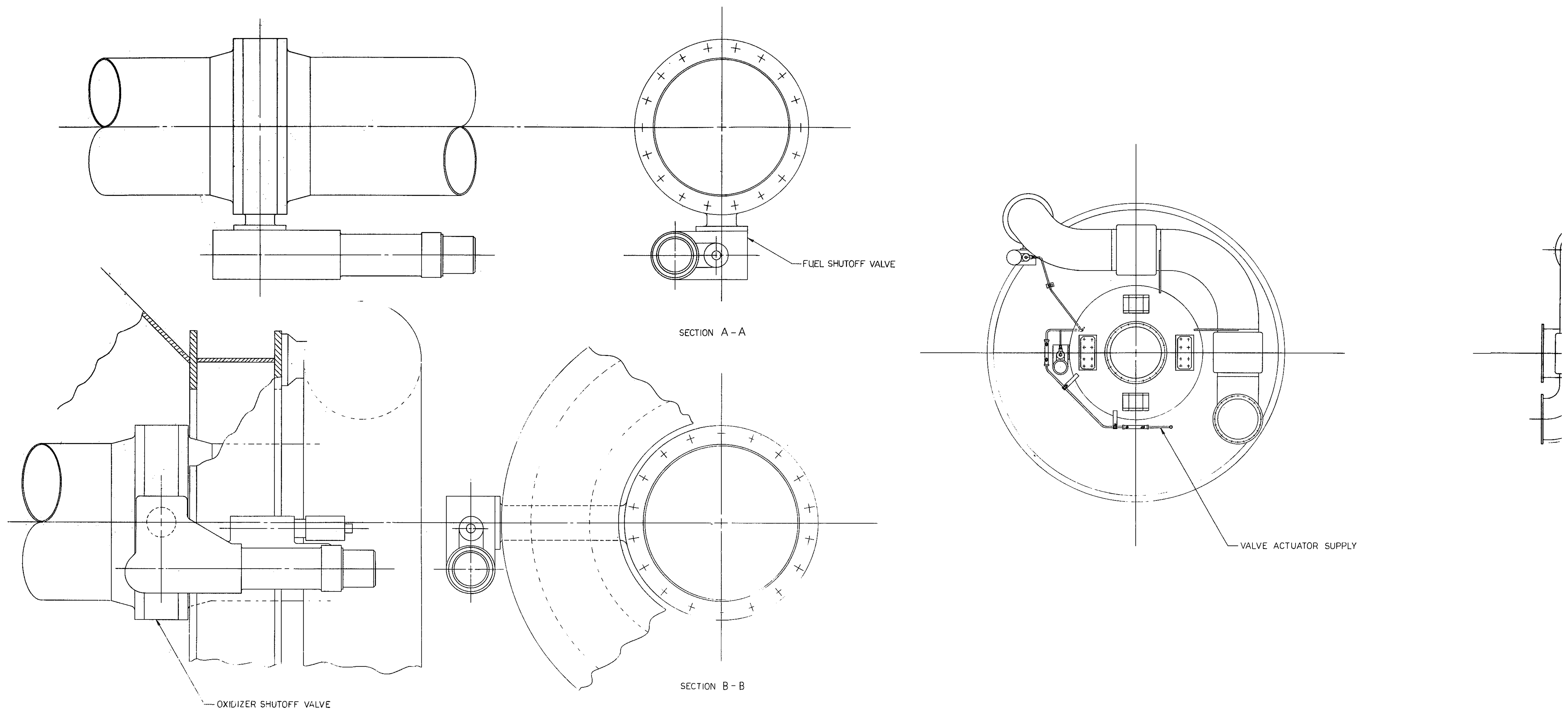


Figure 1.4-1. Exploded View and Photo of Typical Propellant Valve



FUEL SHUTOFF VALVE
SECTION A - A
OXIDIZER SHUTOFF VALVE
SECTION B - B
VALVE ACTUATOR SUPPLY

2

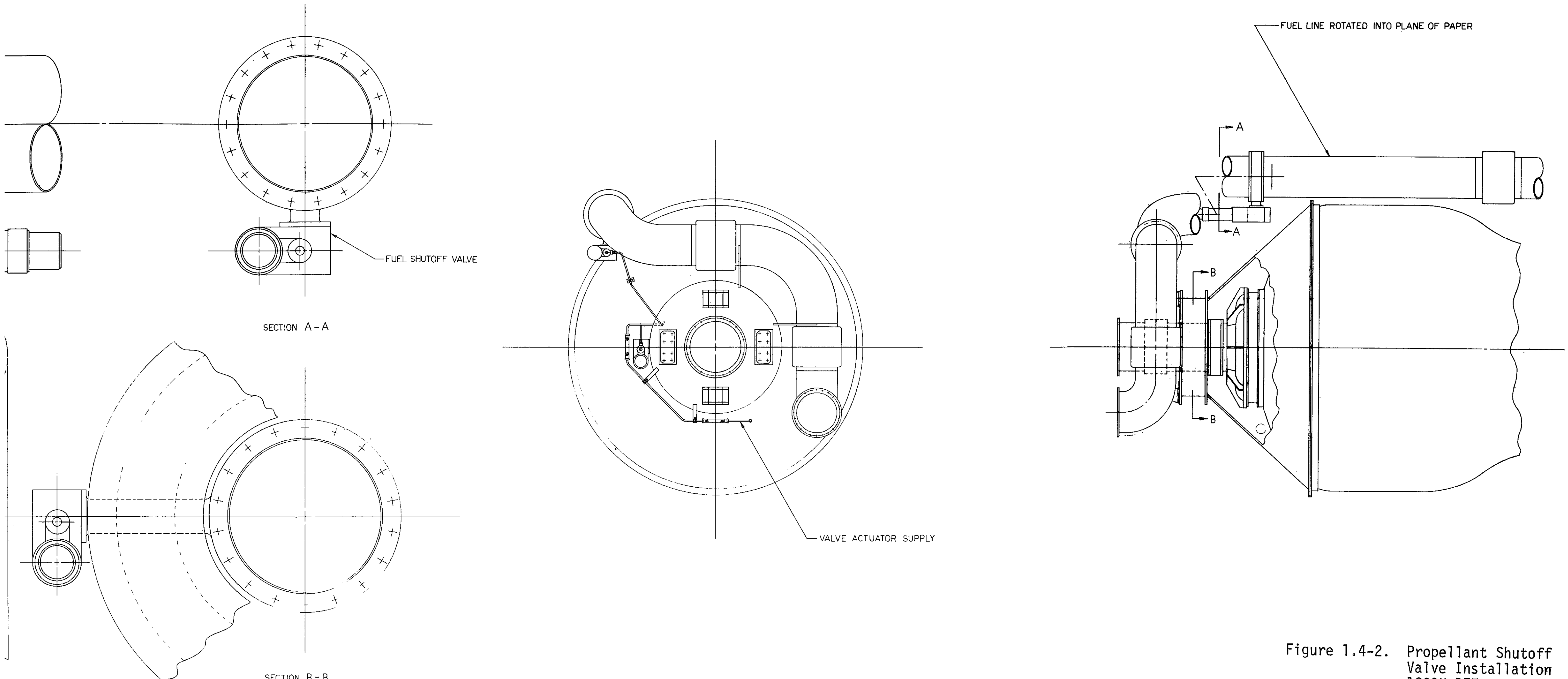


Figure 1.4-2. Propellant Shutoff Valve Installation 1200K PFE

installation is shown in the drawing Figure 1.4-2. Preliminary data indicates the Posiseal design can meet the specified requirements of the system. The valve leak rate of 10 SCIM GN_2 is attainable with minimum development. Life data for a 24" valve in LN_2 cryogenic duty indicates a life of 750 cycles was attained without excessive leakage. Experience presented by the vendor is provided in Table 1.4-1.

The industrial version of the valve, utilizes plain sleeve trunion bearings and a body retained butterfly seal with a contacting wear ring backed up by a flexible loading device. An elastomer ring is used in the normal temperature application and a metal spring member for cryogenic use. A Kel F wear ring is proposed for both LOX and RP-1 applications.

For the industrial version of the valve the peak torque requirement occurs on going in or out of the seal. Both seal and bearing torques at maximum pressure differential are sustained. These fricition torque values far over shadow the hydraulic unbalanced torque typically experienced at the 70 degrees open region of operation. The peak torque at the closed end of the stroke at cryogenic temperature sizes the actuator for the oxidizer side. Based on a potential need for a greater torque to facilitate timing of the fuel valve and potential lower cost of common parts, identical actuators are assumed for both applications.

1.4.2 Characteristics

	Oxidizer Shutoff Valve	Fuel Shutoff Valve
Weight	600 lbs	500 lbs
Envelope Dimension	20" Dia. x 4" Valve 6" x 10" x 26 Actuator	18" Dia. x 4" Valve 6" x 10" x 26 Actuator
Flowrate	3770 lb/sec	1570 lb/sec
Pressure Drop	5 PSID	5 PSID
Actuator Electrical Power Required	60 watts	60 watts
Port Size	16" Dia.	14" Dia.
Leakage	10 SCIM GN_2	10 SCIM GN_2
Design Pressure	360 PSI Nominal	380 PSI Nominal
Opening Time	2.8 sec	1.5 sec
Closing Time	1.0 sec	1.25 sec

Table 1.4-1. Typical Current Commercial Valve Applications of the Posi-Seal Design

THE TABLE BELOW REPRESENTS A CROSS SECTION OF APPLICATIONS OF THE POSI-SEAL WAFER TRUNNION VALVE DESIGN ILLUSTRATING THE RANGE OF SIZES, PRESSURES AND OPERATING TEMPERATURES. IN ADDITION TO THE SPECIFIC SIZES NOTED, MANY OTHER APPLICATIONS IN THE 1 TO 24 INCH RANGE ARE IN EXISTENCE WITH A RANGE OF PRESSURES AND TEMPERATURES.

Valve Size (in.)	Medium	Application	Seal Material	Temperature Range	Pressure (psi)	Approximate Cycles (to date)	Approximate Time in Service No Failure or Leakage to Date
8	LNG	Shutoff Valve	KEL-F	Ambient to -258°F	25	30	2-1/2 years
12	LN_2	Shutoff Valve	KEL-F	Ambient to -320°F	600	52	1 year
24	LN_2	Block Valve	KEL-F	Ambient to -320°F	300	750	2 years
16	Water	Test Shutoff Valve	Teflon	Ambient	400	50	1 year
18	Water	Shutoff	Teflon	Ambient	700	3500	3 years
20	Steam	Shutoff	Teflon	+350°F	15	Unknown	1-1/2 years
24	Steam & Hot Gas	Shutoff	Metal	+500°F	700	Unknown	
60	Water	Shutoff	Teflon	Ambient	700	Infrequent	

1.5 Gimbal

1.5.1 A detailed approach to the head end gimbal ring is shown in Figure 1.5-1. It incorporates a large but conventional structured ring with spherical bearing pivots. The spherical bearings are the Fabroid surfaced bearings which have clearly demonstrated excellent service with low friction over very long life spans. This approach blends well with the coaxial pintle injector allowing the use of a single oxidizer bellows located inside the ring on the axis of the engine. Two fuel bellows are required for articulation and are located outside the ring on the axis of two adjacent pivot points. The fuel line between the bellows is fixed to the gimbal ring. An external restraining device to prevent bellows extension due to pressure is provided for each fuel bellows, however, the nature of the design elmminates the need for added restraint for the oxidizer bellows. This feature also provides a benefit by reducing structural loads (engine thrust) carried by the gimbal and associated structure by nearly 10%.

1.5.2 Characteristics

Gimbal Angle	$\pm$ 6°
Gimbal Rate	10°/sec
Angular Acceleration	3 rad/sec^2
Thrust Load	2.4 x 10^6 pounds (max. design conditions)
Lateral Load	0.158 x 10^6 pounds (max. design conditions)
Weight	1676 pounds
Bearings	Fabroid
Material	Inconel 718
Envelope	45" O.D. x 21" I.D. x 12" Dia. Cross Section

1.6 Hypergolic Igniter

1.6.1 The ignition concept selected for the PFE is a TEA (Triethylaluminum) hypergolic slug closely coupled to the oxidizer circuit within the injector. This approach was chosen for its proven reliability. The TEA is stored in a cartridge with burst diagrams at either end, which is mounted externally to the injector, Figures 1.6-1 and 1.6-2. The cartridge outlet is ported to a small volume manifold which supplies twelve 0.1 inch diameter orifices spaced around the pintle (see Figures1.2-1). The twelve streams of TEA impinge on 12 of the 36 primary oxidizer streams.

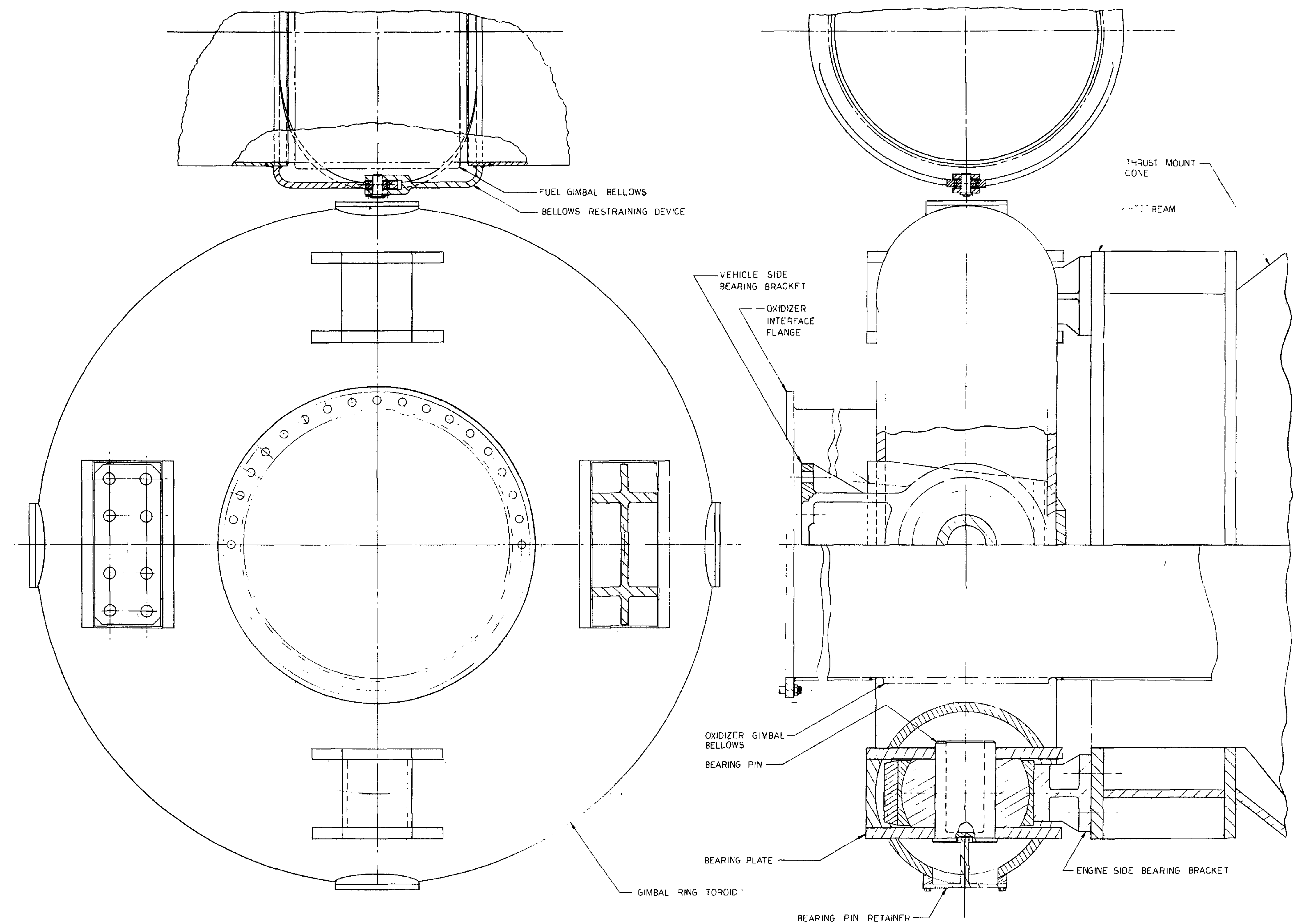


Figure 1.5-1. Gimbal Ring Details

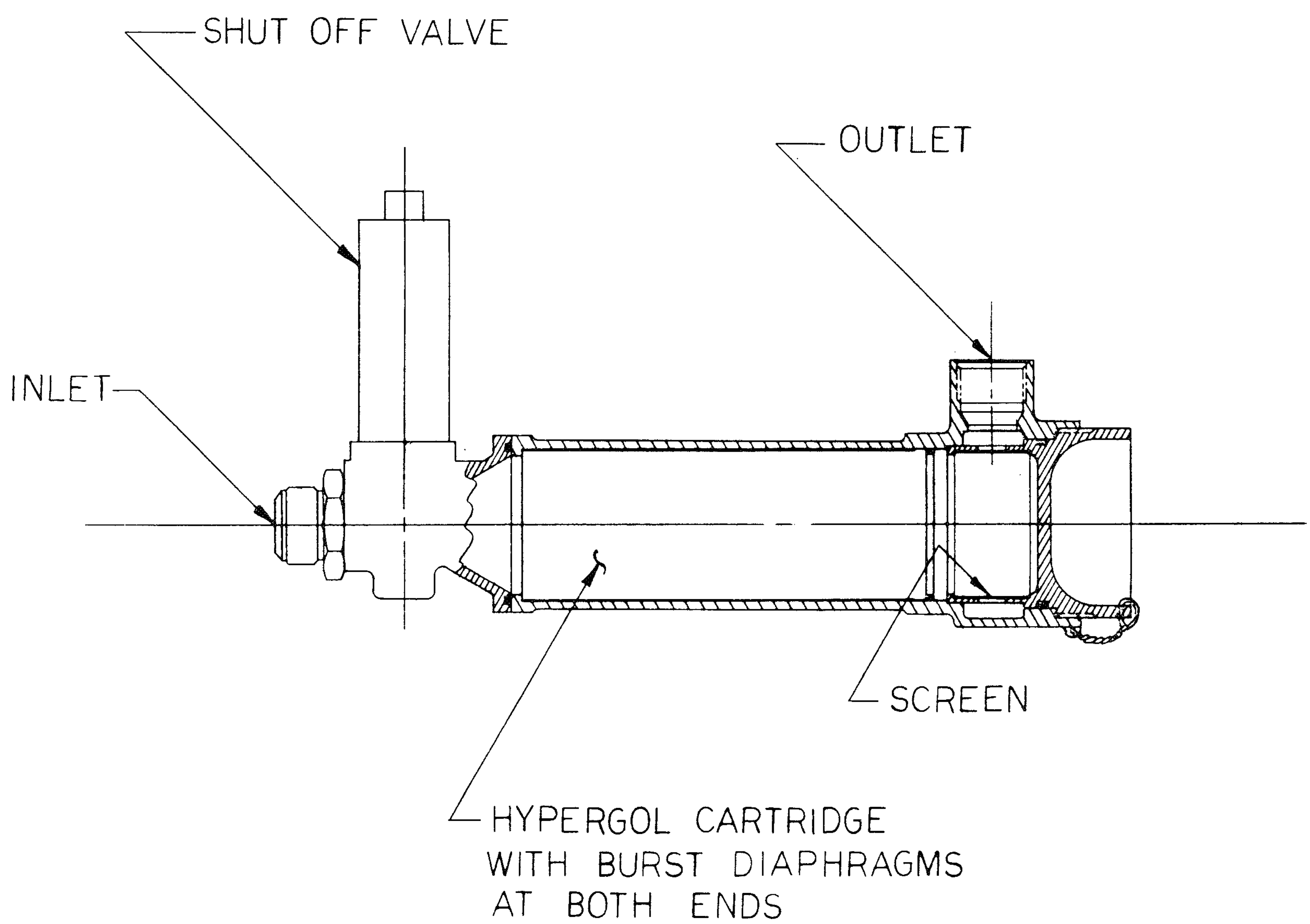


Figure 1.6-1. Hypergolic Cartridge Design

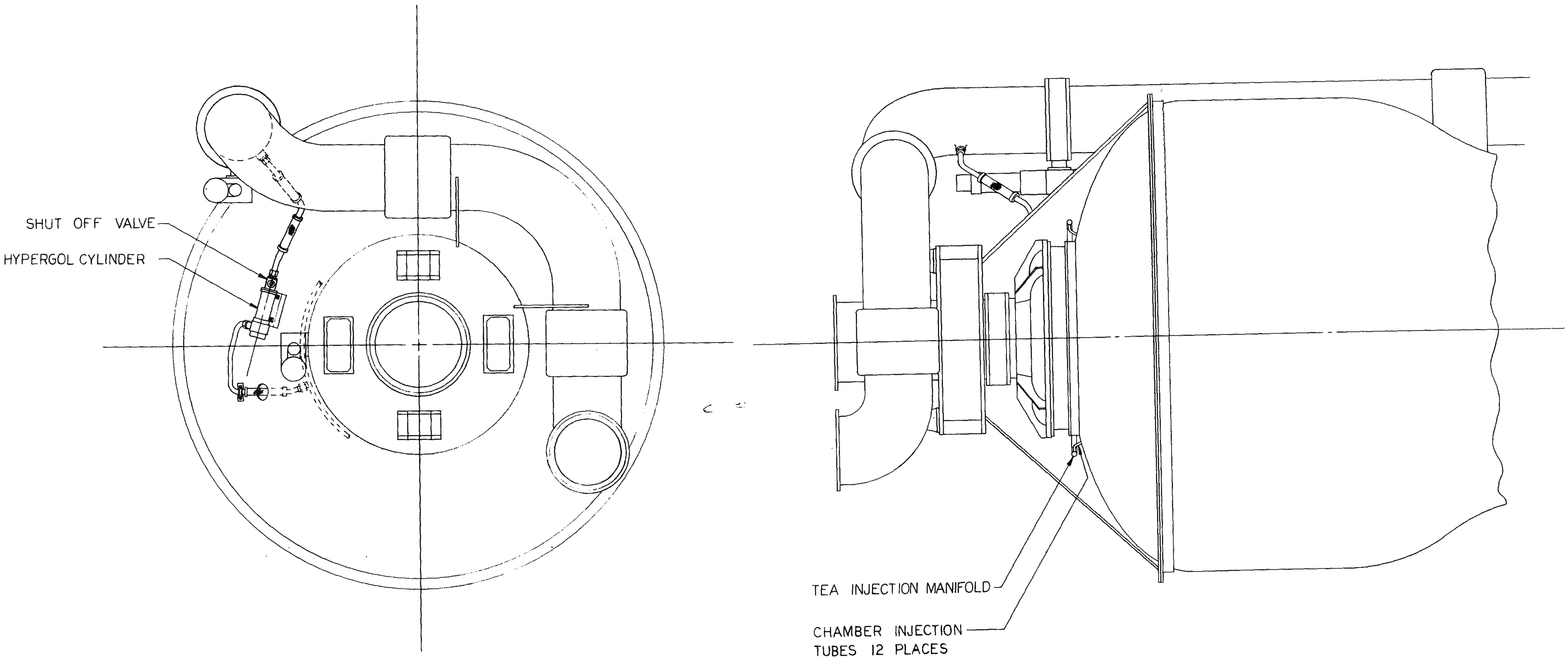


Figure 1.6-2. Hypergol Igniter Installation

Thus, the TEA contacts the LOX very close to the injection orifice outlets, minimizing the volume of LOX accumulated in the chamber prior to ignition. The TEA shut-off valve, integral with the cartridge, is sequenced open at start of opening of the engine LOX valve. The inlet port of the TEA cartridge is supplied with fuel from the main fuel line upstream of the engine fuel valve. The brust discs are actuated by the fuel pressure. After the TEA is expelled from the cartridge and manifold, fuel continues to flow through the TEA injection ports, entering into the mixing and combustion process. Total volume of the TEA manifolding is 30 in^3. The TEA is expelled in less than 1 second.

1.6.2 Characteristics

Length	12.5 in overall
Diameter	2.5 in
Operating Pressure	380 PSIA max.
Weight	15.0 pounds
Power (Valve)	28 watts
Flow Rate	$\sim$1.0 lb/sec

1.7 Propellant Utilization

1.7.1 In order to optimize propellant utilization it is desirable to shift the engine operating mixture ratio during the flight to match the indicated remaining propellants. Several methods of doing this are available as follows:

(1) Fixed mixture ratio settings, i.e. nominal, minimum, maximum.

(2) Continuous open loop mixture ratio control using metering element position as the inner loop control parameter.

(3) Continuous closed loop mixture ratio control using measured flowrates (calculated mixture ratio) as the control parameter.

The engine to engine and run to run variations in engine mixture ratio are discussed in the Final Technical Report. Individual engine manufacturing tolerances will result in 3σ mixture ratio levels about $\pm$ 5%. Flow calibration of each engine will bring nominal mixture ratio within $\pm$ 2%. Random error distributions between engines plus selective engine matching will further reduce the overall vehicle mixture ratio variations resulting from engine variations by $N^{-1/2}$ (N = number of engines = 7). Furthermore, run to run mixture ratio variation excluding propellant supply pressure and temperature variations are well within $\pm$ 0.5%.

The degree of engine mixture ratio accuracy and control required must be determined from a vehicle standpoint. Estimated mixture ratio control limits have ranged from $\pm$ 6 to $\pm$ 16%. Since a minimum of three discrete settings is required it is necessary to incorporate a flow metering device with three settings. The fuel flowrate is the recommended controlled parameter. Mixture ratio is equally sensitive to fuel and oxidizer flowrate variations but thrust is less sensitive to fuel flowrate by a factor of the nominal mixture ratio.

Discrete mixture ratio control can be achieved with the TRW coaxial injector without the necessity of breaking into the fuel feedline. A separate injector fuel sleeve is used which opens up or closes down the fuel injector passage. It is operated by a 3-position, open center, solenoid actuated pilot valve to control fuel flow and provides the added capability of maintaining oxidizer to fuel momentum ratios whereas other methods can result in wide uncontrolled shifts in injection conditions. This approach is recommended for mixture ratio control whether discrete point or continuous mixture ratio control is required. If the mixture ratio setting will be continuously updated it is also desirable to use the open loop controlled position rather than measured flowrate. For fixed propellant supply conditions the additional complexity of adding flow measurement devices plus mixture ratio calculation circuits do not seem to be justified by the small improvement in accuracy. However, variations in propellant temperatures and pressures may result in errors greater than can be accounted for by P.U. systems which determine the remaining propellant at only 10 or so discrete points in the flight.

The use of coaxial injector for P.U. control has an added advantage if engine throttling is required. Mechanical throttling of the injector is accomplished by a moveable sleeve which regulates both propellant flowrates. Again injection conditions can be optimized for each throttle point. Incorporation of the P.U. fuel sleeve within the same mechanism provides a further capability for trimming the fuel side to optimize performance. Figure 1.7-1 shows, for example, relative positioning of the two seleves to throttle the engine. This positioning is most easily accomplished by position control loops on each sleeve. As mixture ratio is shifted only the fuel sleeve is adjusted. Inclusion of both throttling and P.U. control

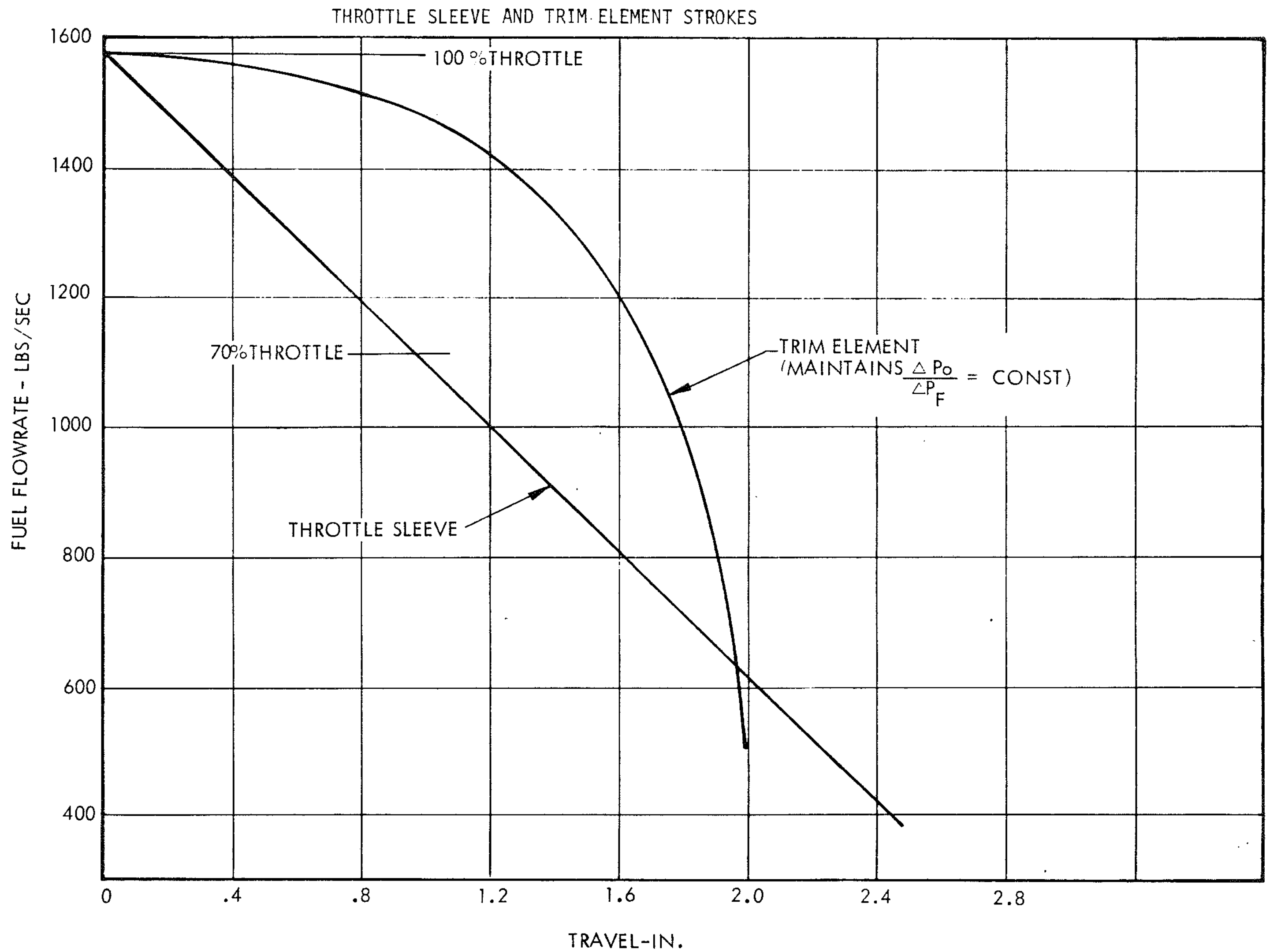


Figure 1.7-1. Pressure Fed Engine

within the injector element requires the same additional hardware as separate upstream valves and has the overriding advantage of providing optimum injection conditions at all operating points.

1.7.2 Characteristics

M.R. Control	± 20%
Throttle Control	30%
Face Shut Off	Capable
Power (Electrical)	28 watts

2.0 ALTERNATE TVC

During the early portion of the study program, two alternate approaches to Thrust Vector Control were considered; secondary injection using one of several injectants, and a swivel nozzle configuration utilizing the UTC patented Techroll® Fluid Bearing. Each of these approaches have certain attractive features and each results in an engine configuration which satisfies all of the basic engine requirements.

A weight comparison among the three TVC configurations is presented in Table 2.1-1.

2.1 Secondary Injection

2.1.1 Secondary Injection Manifolding Into PFE

During the PFE study program, consideration was given to how a secondary injection system could be manifolded to pass the injectant through the primary coolant tube bundle. The results of the effort are shown in Figure 2.1-1. The primary coolant tube bundle is itself manifolded in the area of the secondary injectant valves. The exit plane to manifold coolant tubes are terminated in this secondary fuel manifold which is continuous circumferentially about the nozzle and extends for about four inches along the nozzle. Fuel manifold to injector tubes pick up the coolant fuel at the manifold and then carry it to the injector. The circumferential fuel manifold is machined on the outside to accept the secondary injection valves. Ports through the manifold carry the secondary injectant flow into the hot gas stream within the nozzle. The continuous manifold approach allows for increased nozzle stiffening, and it eliminates a troublesome feed passage problem for the coolant and the cooling of the SITVC ports.

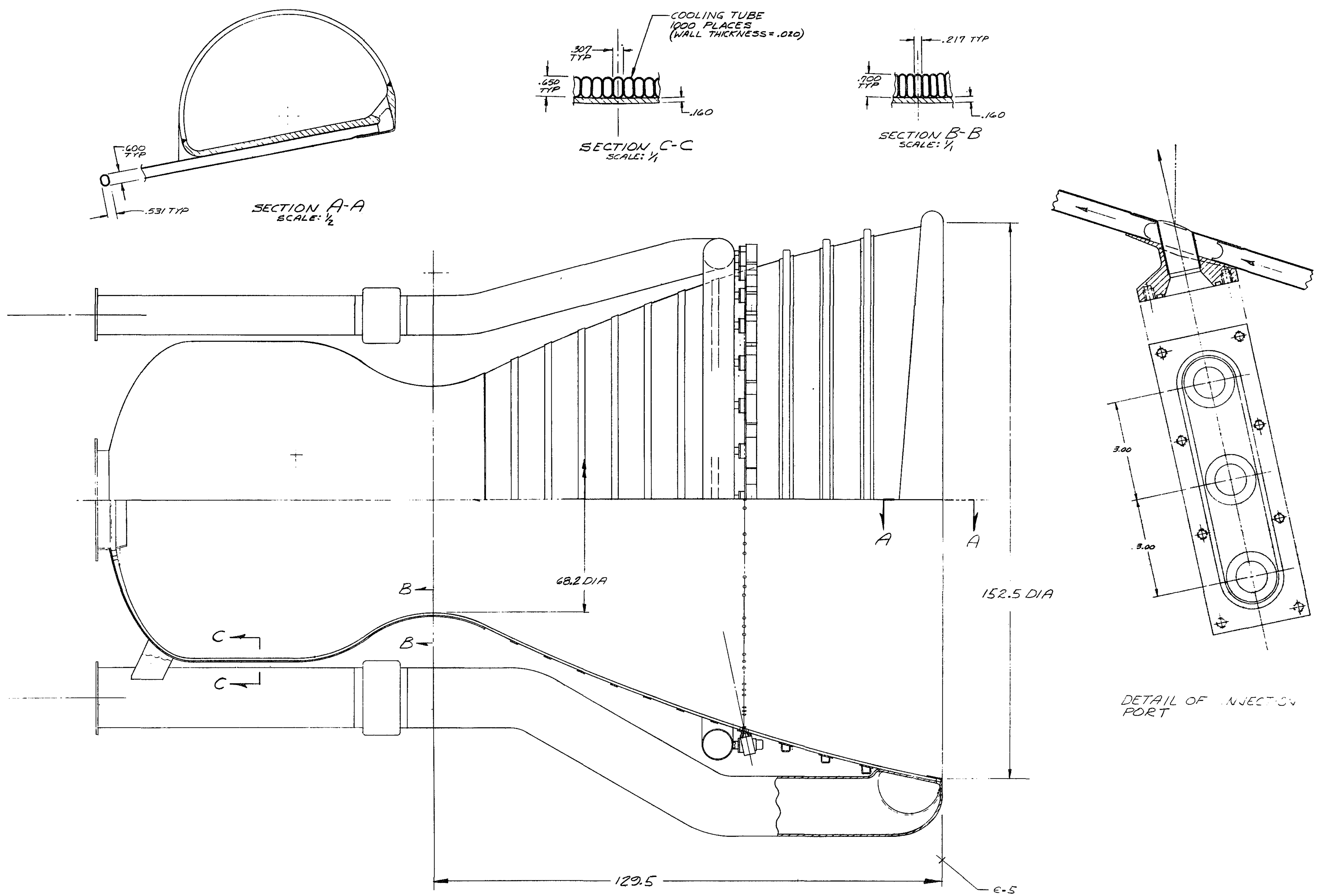


Figure 2.1-1. Secondary Injection Manifold Detail

TABLE 2.1-1 Weight Comparison - TVC Configuration

	Gimbal	LITVC	Swival Nozzle
Engine Dry Weight	11,467	11,561	12,279
Residual Fuel	3,152	2,859	1,952
Residual Oxidizer	337	1,755	337
TOTAL WET WEIGHT	14,956	16,175	14,562

2.1.2 LITVC Valves

The LITVC performance analysis including a comparison of various injectants and injection techniques is presented in the Final Technical Report. As a result of these studies the use of RP-1 was recommended due to the minimum complexity and therefore, highest system reliability and the lowest system development risk. A summary of the side specific impulse versus thrust vector angle is presented in Figure 2.1-2 for a 5:1 nozzle. The performance calculations are based on multiple orifice injection at an expansion ratio of about 3:1. The resulting injectant weights and volumes per engine are presented in Figures 2.1-3 and 2.1-4 as a function of total axial impulse and a 1° average deflection angle. The resulting duct and manifold sizes as a function of thrust level are presented in Figure 2.1-5. Also shown are the maximum flowrate requirements at the 1.2×10^6 lbf for 5° maximum angle. The RP-1 flowrate at 6° is also indicated. A weight trade-off study was conducted varying the number of valves fired at one time and the total number of valves per engine based on an omni-axis control system. The results as presented in Figure 2.1-6 indicated that a minimum weight is achievable with various combinations. For a 6° deflection angle using RP-1 the total maximum flowrate is 2100 lbs/sec. Based on a comparison of volumetric flowrates a total of 32 valves should be used firing either 6 or 8 at a time to be able to use the largest currently available servoinjector valve. The recommended approach is to fire 6 valves at a given time for optimum performance and enlarge the valves to handle 350 lbs/sec. of RP-1 at 380 psia supply pressure.

A typical valve as shown in Figure 2.1-7 would have three injector pintles mechanically linked and positioned by a servovalve controlled RP-1 actuator operating off of supply line pressure. The valve should weigh on the order of 12 lbs and have a full stroke response of about

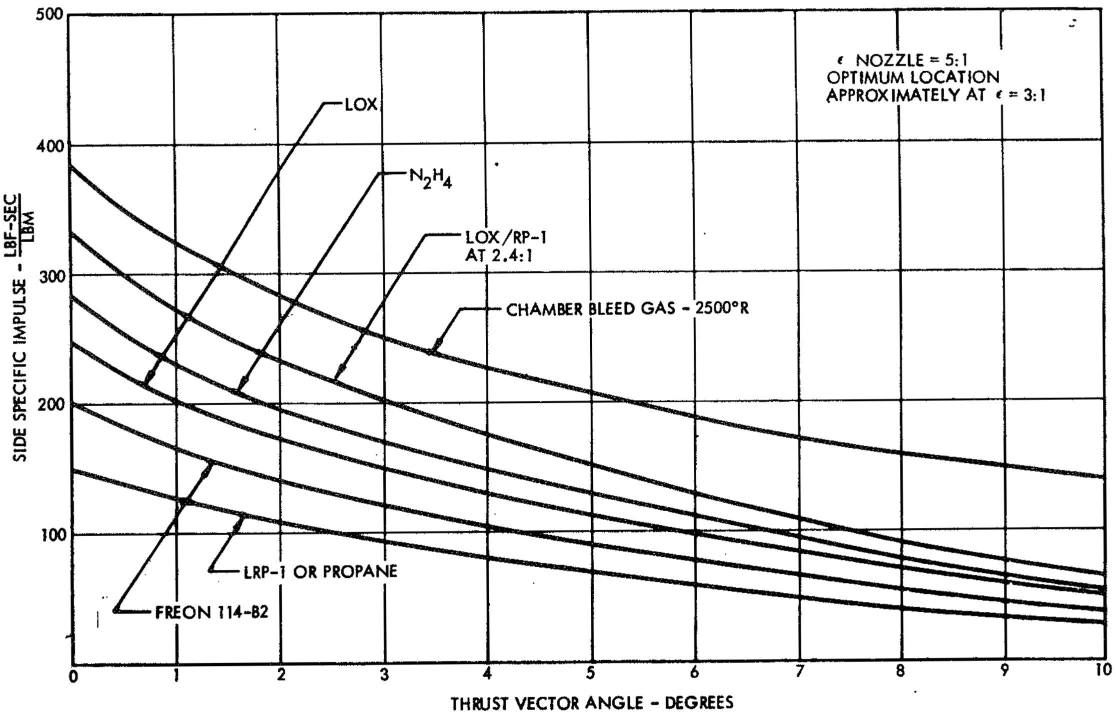


Figure 2.1-2. Multiple Orifice Side Specific Impulse vs. Deflection Angle

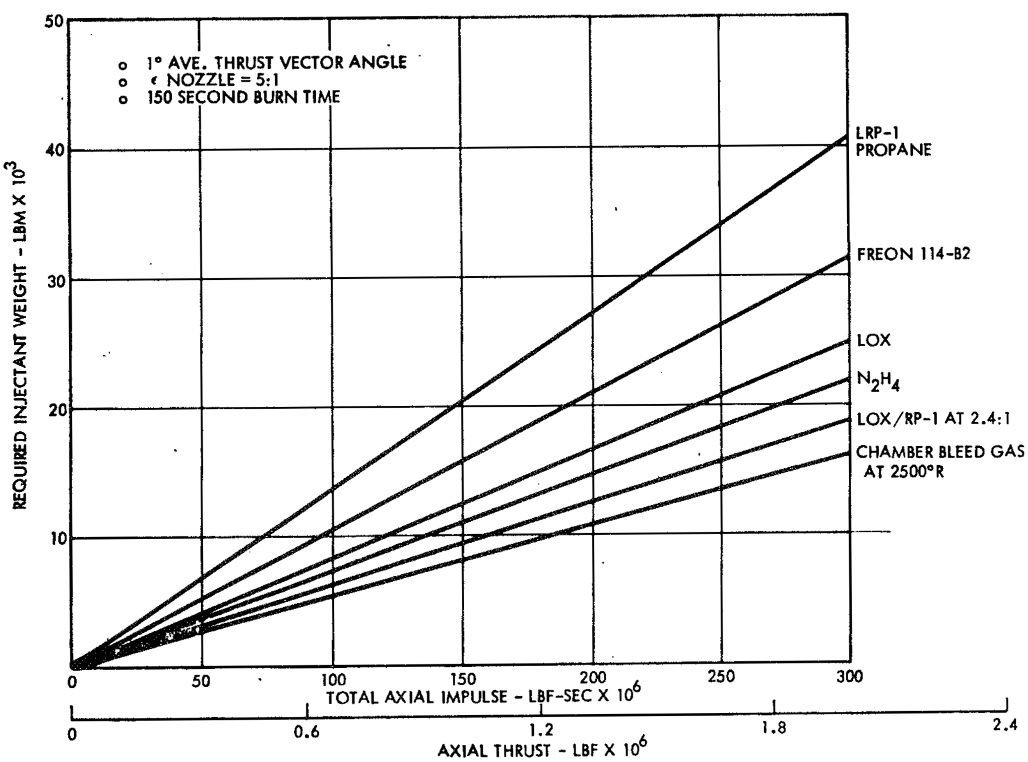


Figure 2.1-3. LITVC Injectant Weight vs. Axial Impulse Per Engine

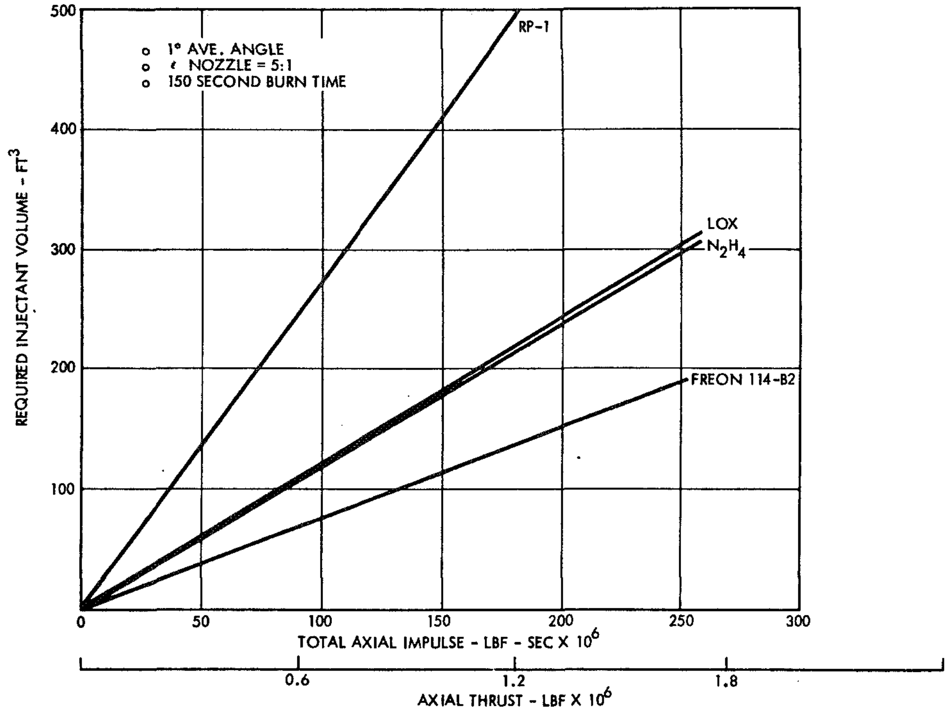


Figure 2.1-4. LITVC Injectant Volume vs. Axial Impulse Per Engine

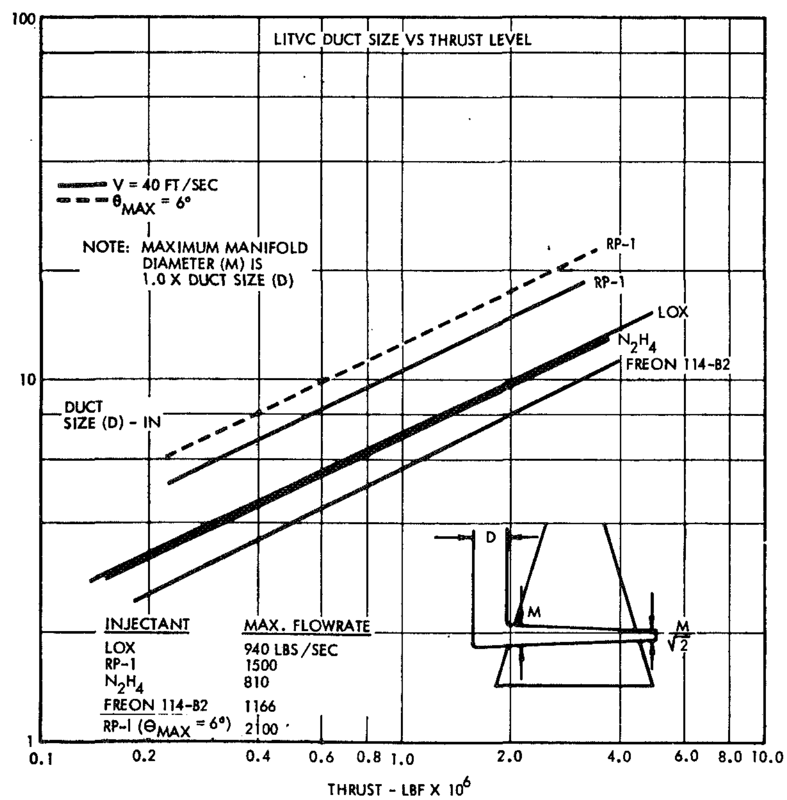


Figure 2.1-5. LITVC Duct Size vs. Thrust Level

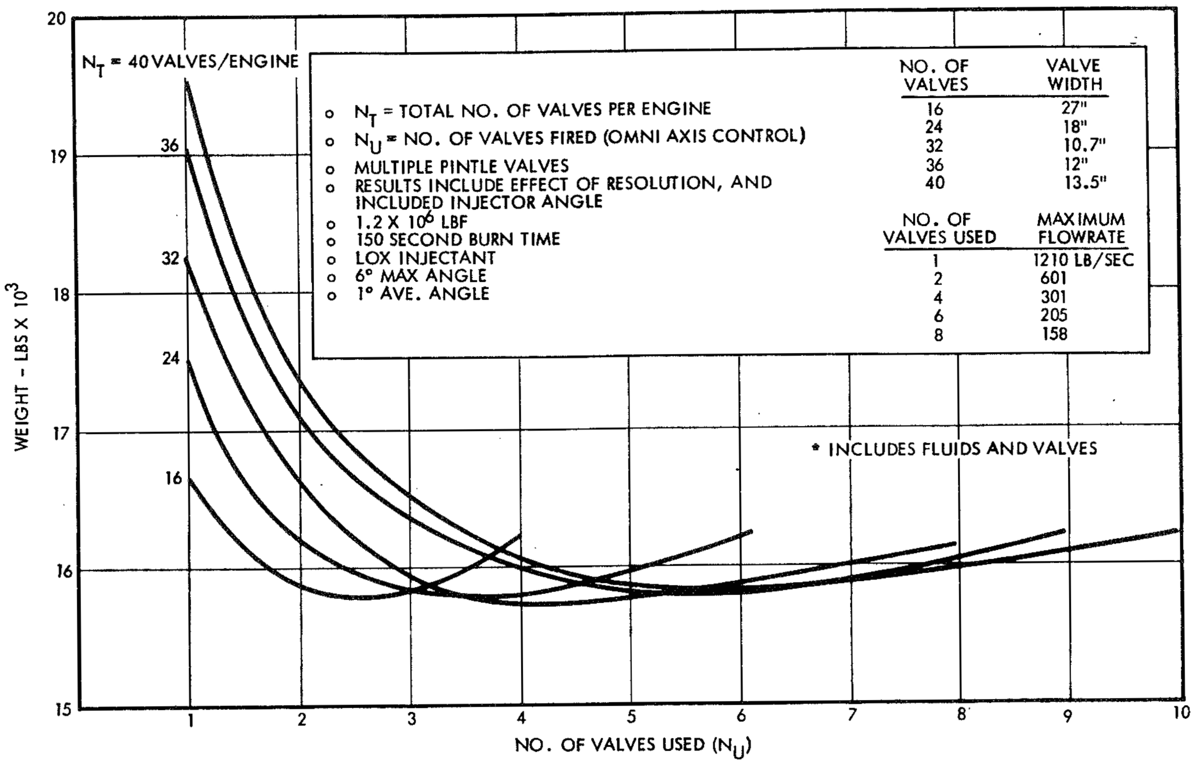


Figure 2.1-6. LITVC Weight* vs. Number of Valves

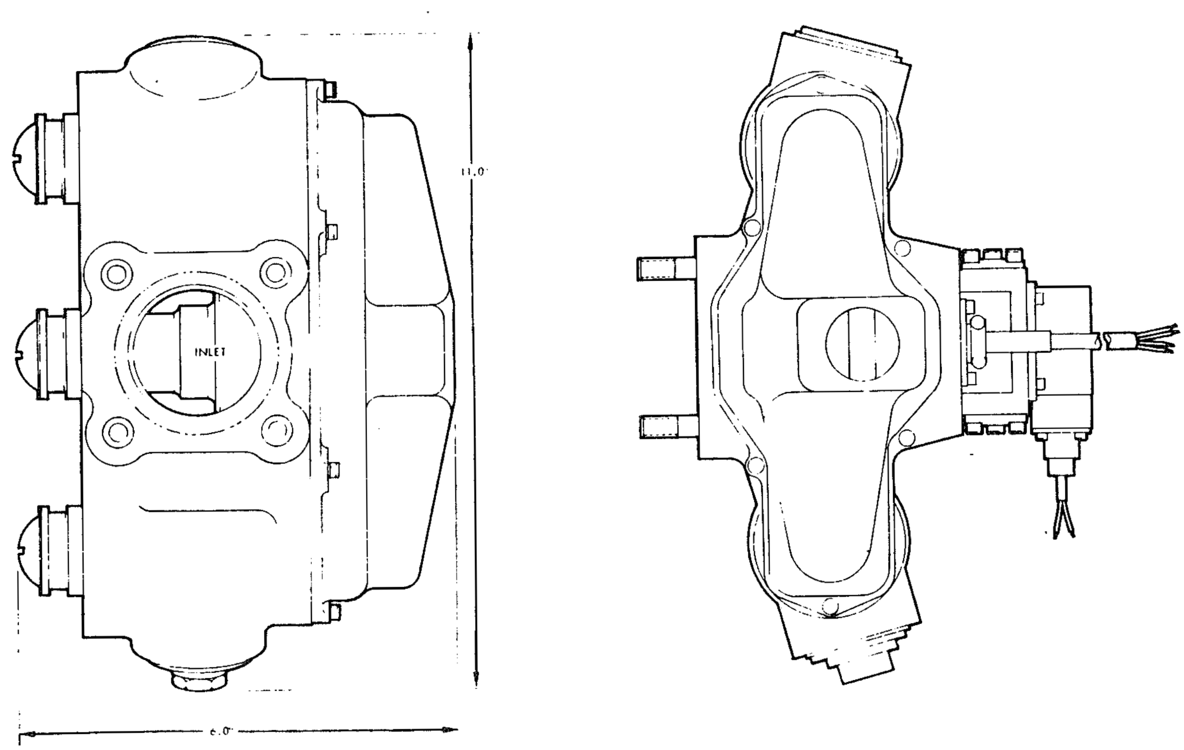


Figure 2.1-7. LITVC Servo Injector Valve

0.37 second to provide the 10 deg/sec. slewrate.

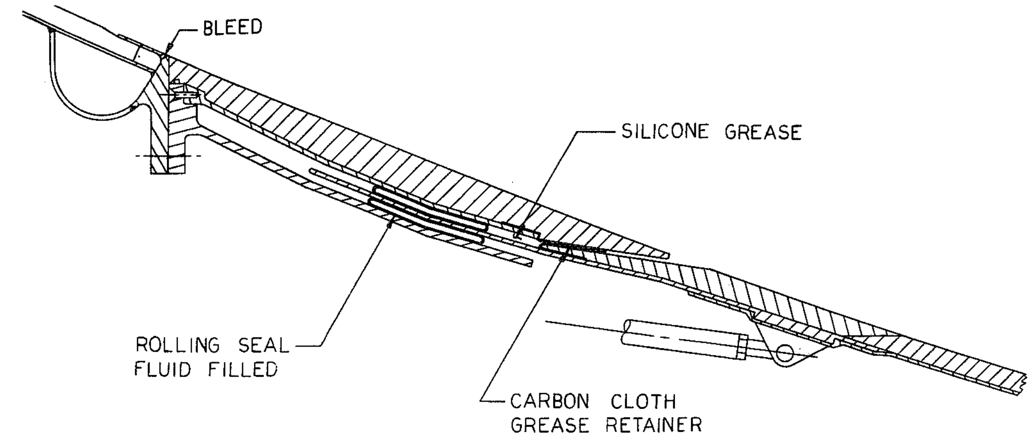
The typical envelope of the LITVC configuration engine is very similar to the static envelope of the gimablled engine shown in Figure 1.1-3.

2.1.3 Swivel Nozzle

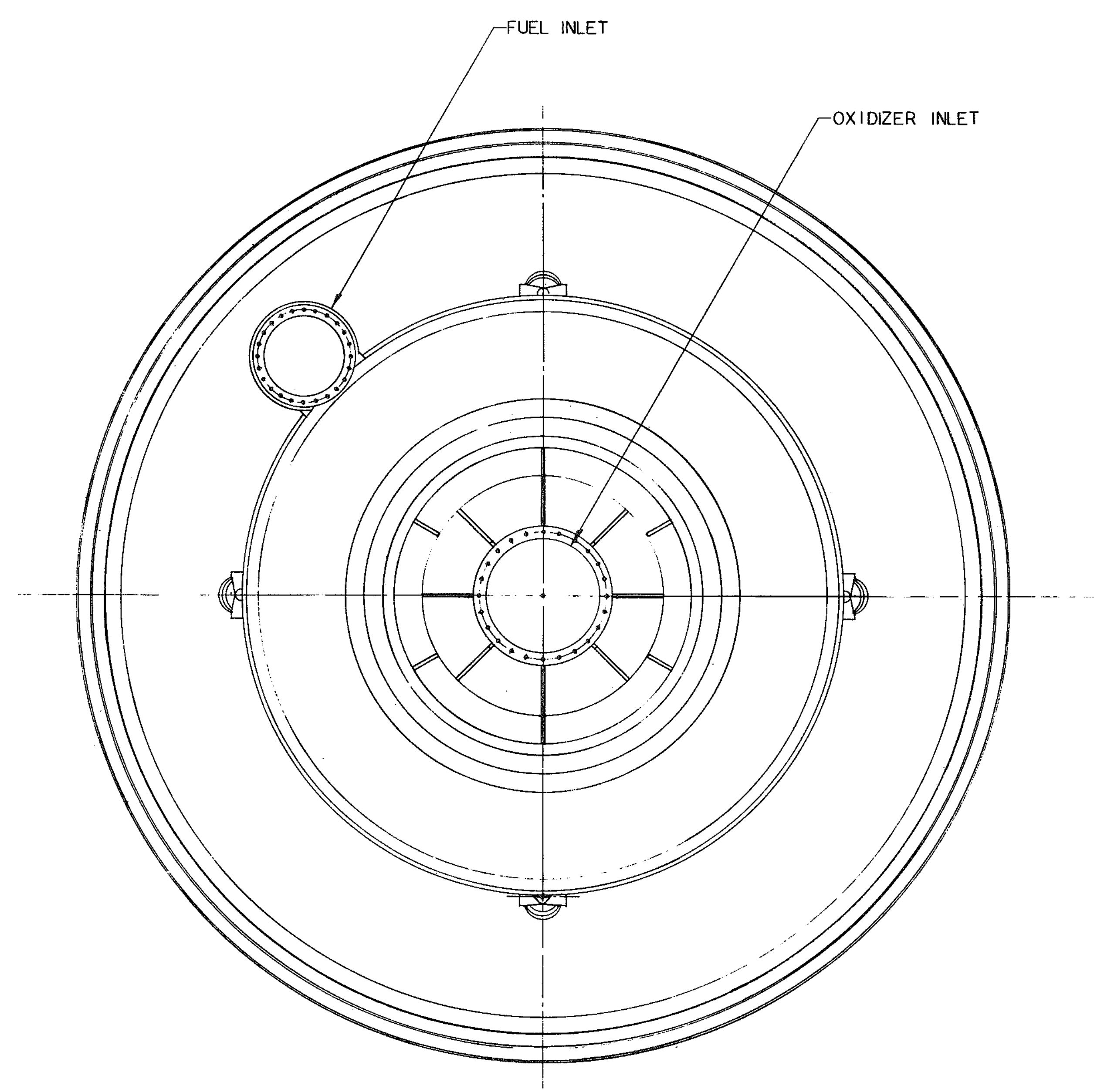
An approach to thrust vector control which shows great promise is to pivot only the nozzle about a point slightly downstream of the throat. The combustion chamber and head end would be fixed to the structure.

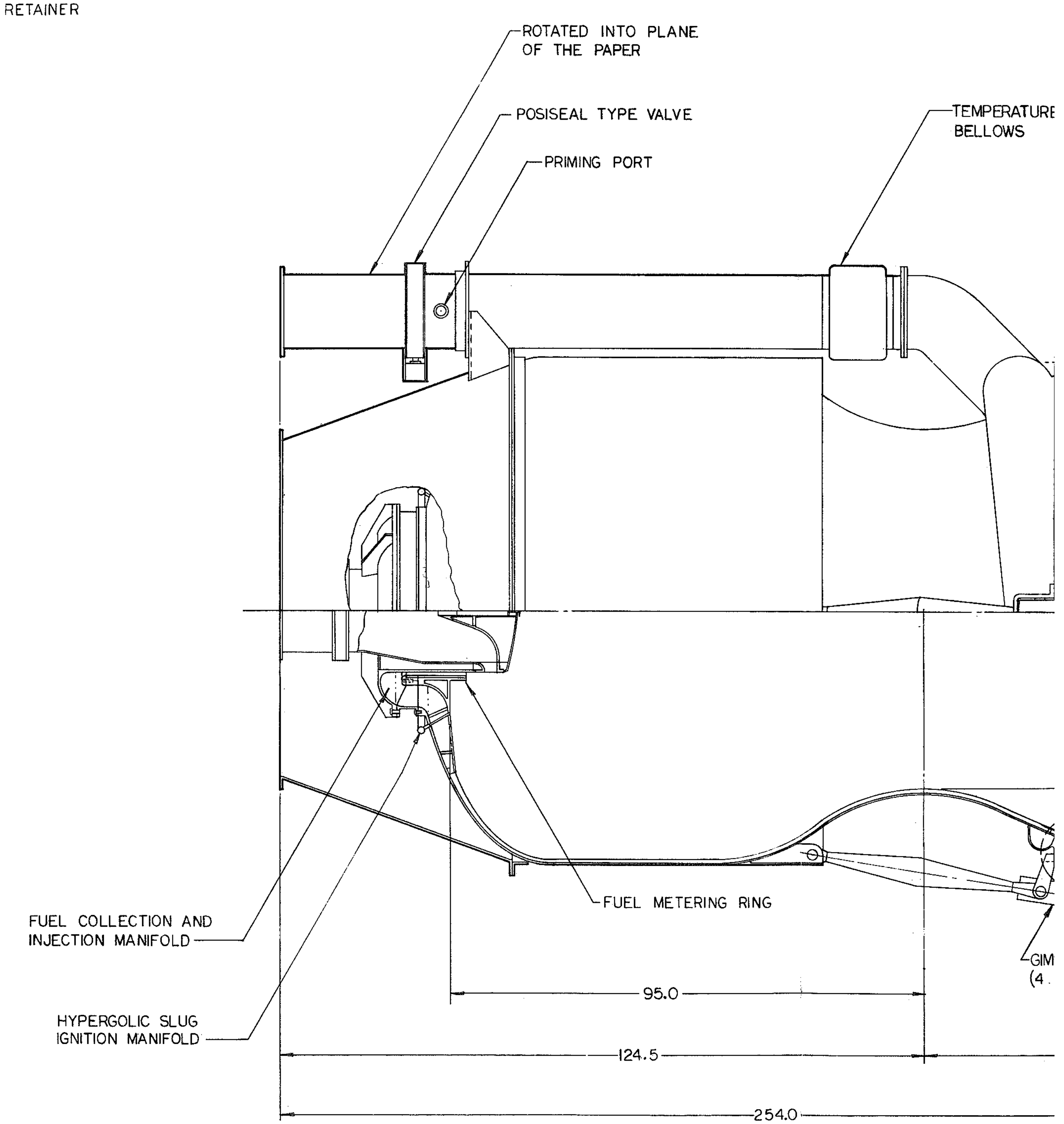
Discussions have been held with United Technology Center regarding the use of the UTC patented Techroll® seal fluid bearing for this application. Although the size of bearing required for this application is many times larger than any yet made, the governing engineering requirements, i.e. unit loading, temperature, angle of deflection, etc., are all well within demonstrated limits for the device. This application imposes an environment which is, in fact, far less severe than already demonstrated.

A swivel nozzle using the Techroll® seal is shown in Fgiure 2.1-8 with an ablative nozzle pivoted on the Techroll® fluid bearing and actuated by four hydraulic cyliners. The static and dynamic envelopes are also indicted in Figure 2.1-9. The nozzle being ablative, is consumed during each mission and needs replacing after each flight.


BLEED
SILICONE GREASE
ROLLING SEAL
FLUID FILLED
CARBON CLOTH
GREASE RETAINER

DETAIL A


FUEL INLET
OXIDIZER INLET


ROTATED INTO PLANE
OF THE PAPER
POSISEAL TYPE VALVE
PRIMING PORT
TEMPERATURE
BELLOWS
FUEL METERING RING
FUEL COLLECTION AND
INJECTION MANIFOLD
HYPERGOLIC SLUG
IGNITION MANIFOLD
95.0
124.5
254.0

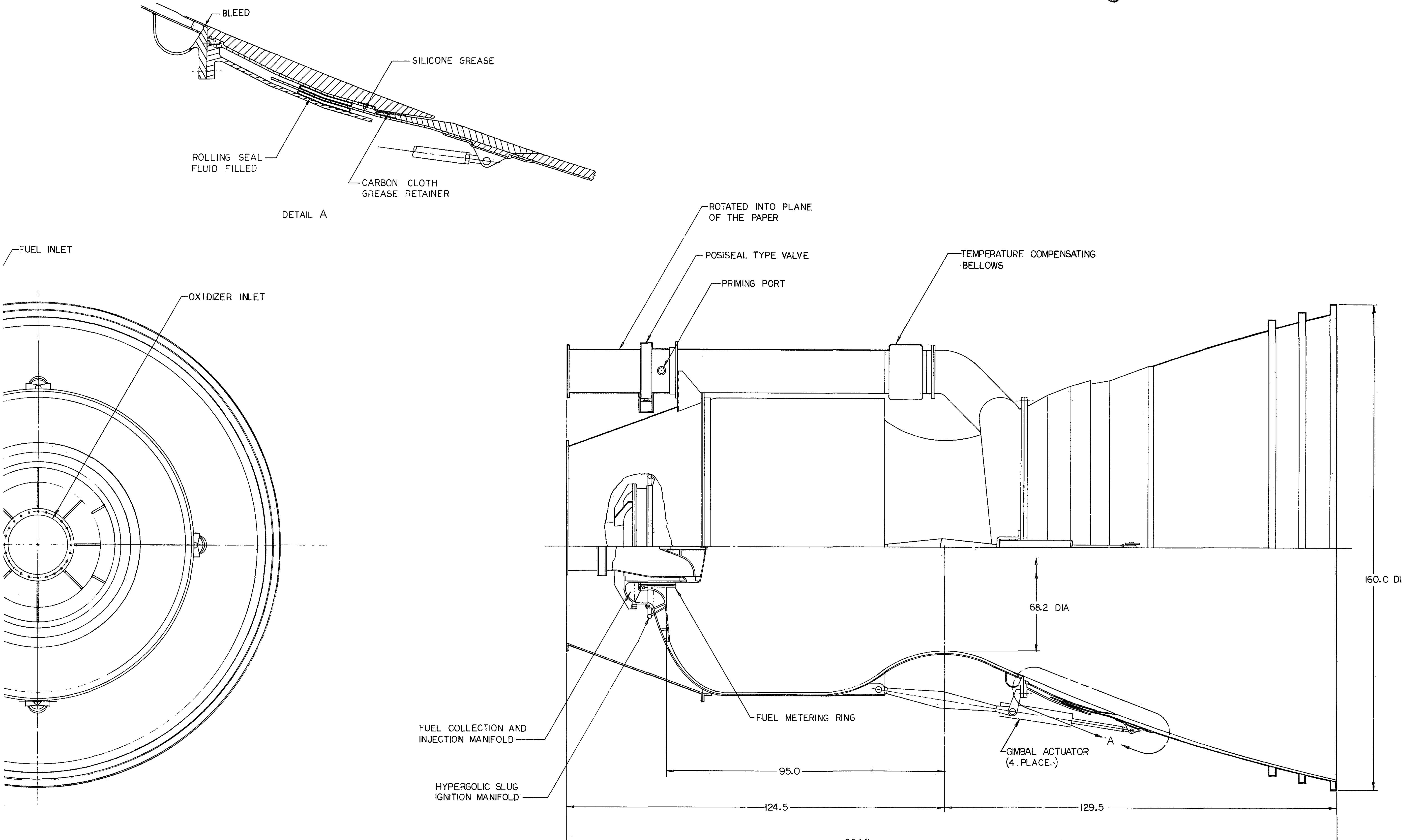


Figure 2.1-8. Swivel Nozzle with Techroll® Fluid Bearing

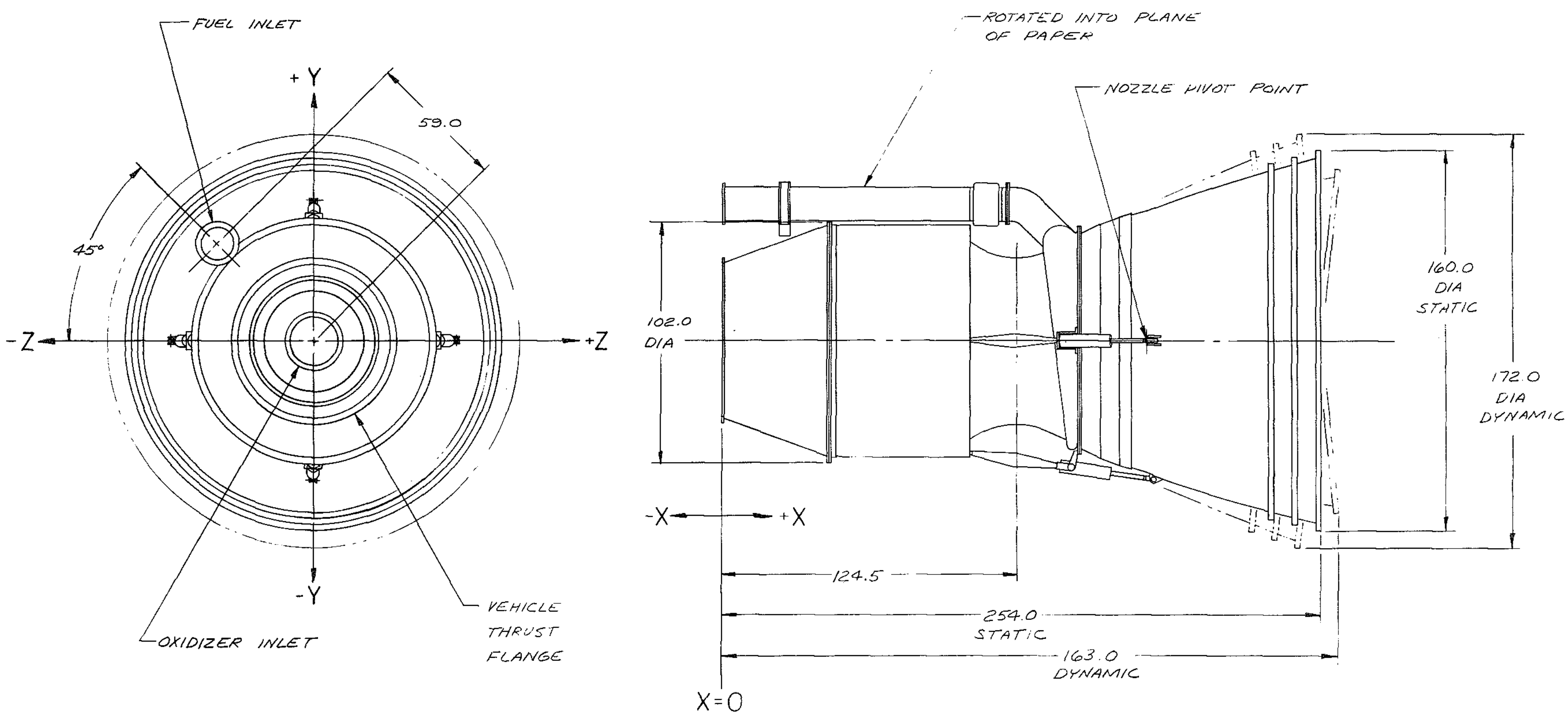


Figure 2.1-9. Static and Dynamic Envelope of Swivel Nozzle Configuration